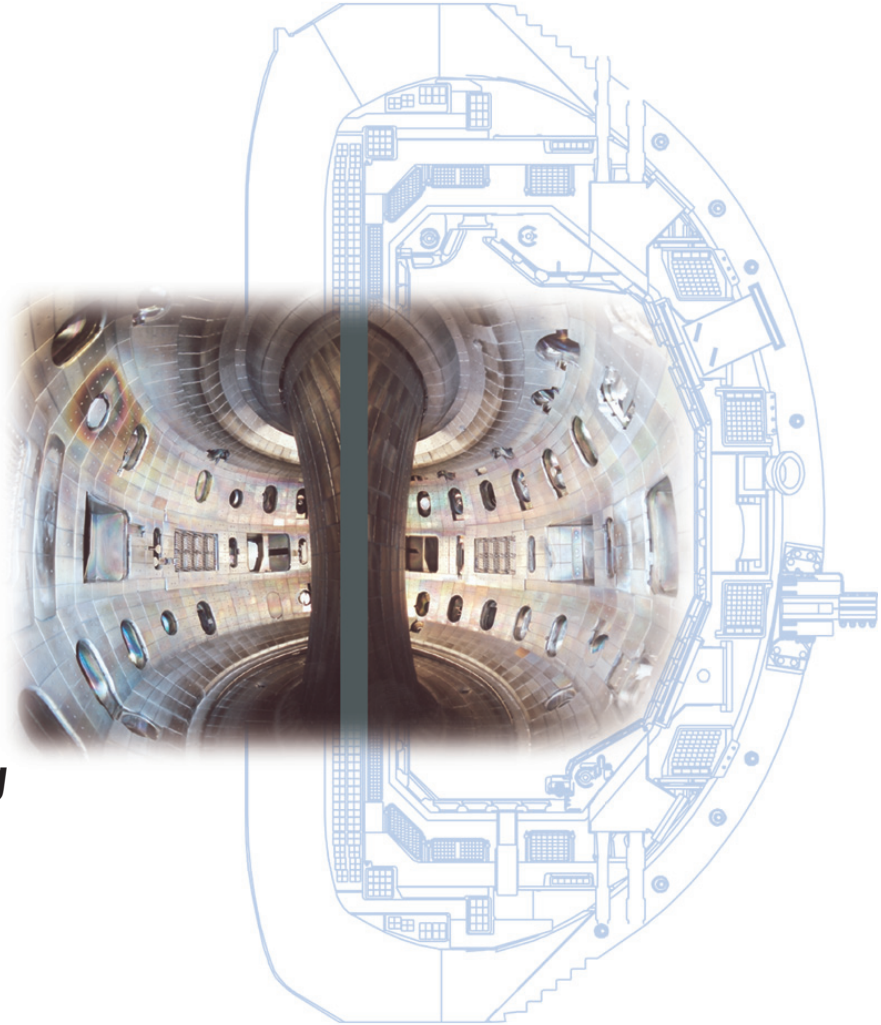
The Six Gyrotron System on the DIII-D Tokamak

John Lohr
Mirela Cengher, Jim Deboo,
John Doane, Yuri Gorelov,
Charles Moeller, Dan Ponce
and Ron Prater

presented at
EC-16
The Sixteenth Joint Workshop on
Electron Cyclotron Emission
and Electron Cyclotron Resonance Heating

Sanya City, China
12-15 April 2010



DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

Outline

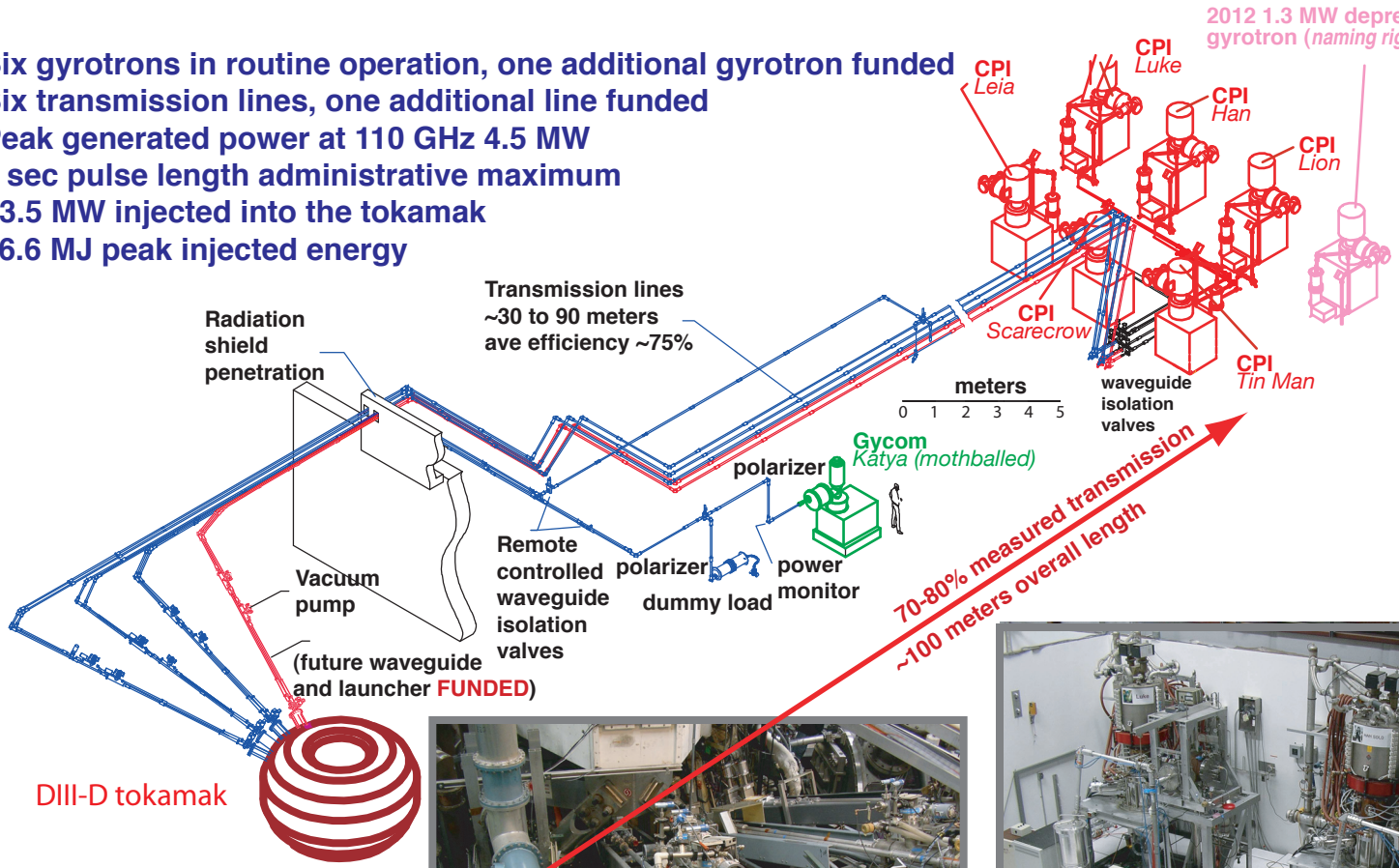
- **Gyrotron system description**
- **Performance data for the 2009-2010 campaign**
- **Selected physics experiments featuring ECH**
  - NTM suppression with real time poloidal steering control
  - Modulated temperature gradient transport study
  - Startup
- **Gyrotron system related experiments and techniques**
  - Optical spectrometer measurements
  - Using DIII-D bolometers to measure injected power
  - RF/waveguide alignment
  - Low frequency parasitic emission
- **New hardware**
  - Power and polarization monitor
  - FPGA controls
  - Helium reliquifier
- **System upgrade**
  - 1.2 MW gyrotron
  - Addition to gyrotron vault
  - Waveguide rerouting
- **Long term plans**
- **Summary**

Outline

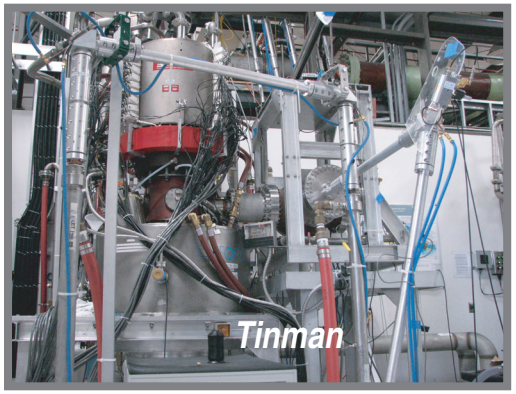
- **Gyrotron system description**
- **Performance data for the 2009-2010 campaign**
- **Selected physics experiments featuring ECH**
  - NTM suppression with real time poloidal steering control
  - Modulated temperature gradient transport study
  - Startup
- **Gyrotron system related experiments and techniques**
  - Optical spectrometer measurements
  - Using DIII-D bolometers to measure injected power
  - RF/waveguide alignment
  - Low frequency parasitic emission
- **New hardware**
  - Power and polarization monitor
  - FPGA controls
  - Helium reliquifier
- **System upgrade**
  - 1.2 MW gyrotron
  - Addition to gyrotron vault
  - Waveguide rerouting
- **Long term plans**
- **Summary**

DIII-D 110 GHz six gyrotron system

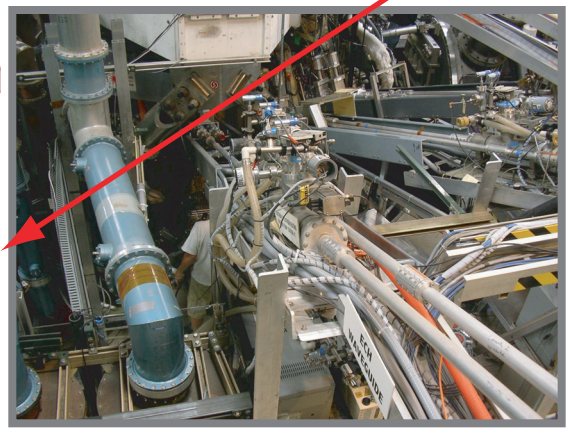
Six gyrotrons in routine operation, one additional gyrotron funded
Six transmission lines, one additional line funded
Peak generated power at 110 GHz 4.5 MW
5 sec pulse length administrative maximum
~3.5 MW injected into the tokamak
16.6 MJ peak injected energy



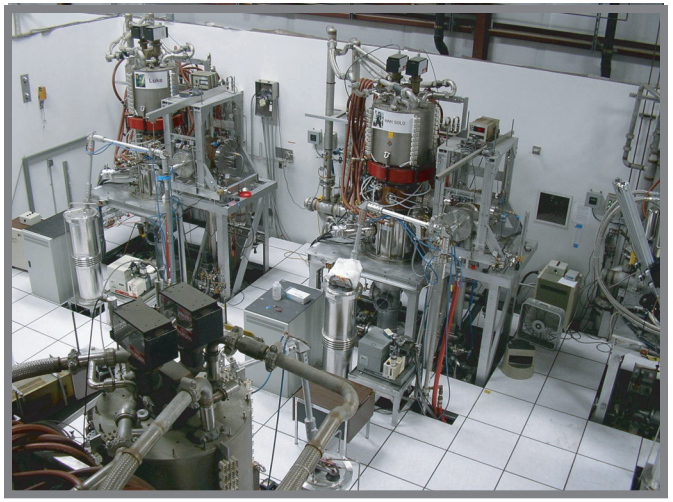
110 GHz gyrotron



1.3 MW prototype depressed collector 7th gyrotron



Waveguides and vacuum system in DIII-D machine pit



ECH gyrotron vault

Gyrotrons on DIII-D

CURRENT DIII-D SYSTEM GYROTRON PARAMETERS

Gyrotron	Manufacturer	Date	P_{GEN}/τ (MW/s)	Operational Status/History
Scarecrow	CPI	2000	0.85/5	Normal operation. The gyrotron had its window replaced after corrosion failure of the aluminum seal and later had its collector replaced after a large water leak developed.
Tinman	CPI	2000	0.85/5	This gyrotron had a small leak in the bottom of the collector, which limited performance. The tube has been repaired at CPI, conditioned at DIII-D and is in regular service.
Lion	CPI	2002	0.85/5	This gyrotron had a collector failure with substantial overheating, slight buckling of the structure and extensive stress cracking on the hot sides of the cooling tubes. Repair was completed and the gyrotron is in regular service at DIII-D.
Luke	CPI	2005	0.85/5	This gyrotron is in regular, reliable service at DIII-D
Han	CPI	2006	0.7/5	In regular, reliable operation at DIII-D. The tube generates ~750 kW, rather than 1.0 MW for unknown reasons.
Leia	CPI	2007	0.85/5	This gyrotron is in regular, reliable service at DIII-D.

All gyrotrons at operating at DIII-D except Han passed acceptance tests at >950 kW and 5 sec pulse length for 10 consecutive pulses. Operational power is lower to enhance the reliability, particularly for pulses >2.5 sec.

Immediate future plans:

A 1.3 MW 110 GHz, 10 sec depressed collector gyrotron has been placed on order and funding has been received for its HV power supply, controls, transmission line, launcher and an extension to the ECH vault area.

DIII-D RETIRED GYROTRON OPERATIONAL HISTORIES

Gyrotron	Manufacturer	Date	P_{GEN}/τ (MW/s)	Operational Status/History
Katya	Gycom	1996	0.6/2.0	On standby, not operating; cathode efficiency was slowly decreasing, but operation was reliable with P_{GEN}~600 kW. Katya is semi-retired but could be returned to service if required. May go to KSTAR.
Boris	Gycom	2000	0.75/2.0	Gyrotron removed from service in good condition and installed and operating on KSTAR for breakdown assist and transition to equilibrium. P_{GEN}~750 kW with full HV and current.
Natasha	Gycom	2000	0.5/2.0	Retired/vacuum failure. Probably can be repaired if desired.
Chewbacca	CPI	2006	1.3/short	This gyrotron was the first 110 GHz CPI gyrotron with a depressed collector. Chewy completed testing at CPI. 1.25 MW short pulse, >500 kW, 10 sec pulses. The tube was installed at DIII-D and being operated at low power without rf generation when it developed a collector leak. The design, with a new CrZrCu collector and other improvements, is the basis for the next gyrotron for DIII-D.

Longer term plans:

It is hoped that an additional gyrotron will be funded that uses some of the infrastructure already built for the 7th tube. This may be a slightly higher frequency, say 117 GHz and power, ~1.5 MW depressed collector tube.

Ultimate plan:

Upgrade to 10 gyrotrons with ≥ 1.5 MW unit power, 10 sec pulse length possibly with a mix of frequencies.

Outline

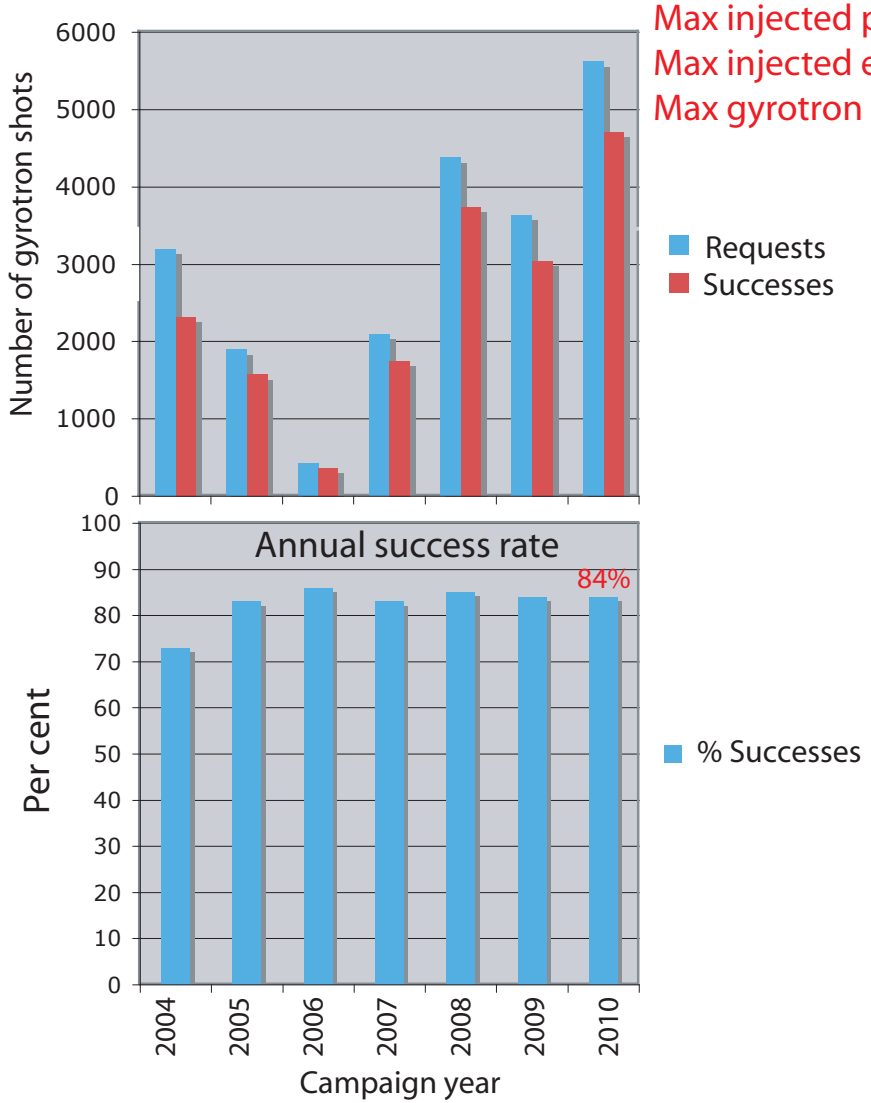
- **Gyrotron system description**
- **Performance data for the 2009-2010 campaign**
- **Selected physics experiments featuring ECH**
  - NTM suppression with real time poloidal steering control
  - Modulated temperature gradient transport study
  - Startup
- **Gyrotron system related experiments and techniques**
  - Optical spectrometer measurements
  - Using DIII-D bolometers to measure injected power
  - RF/waveguide alignment
  - Low frequency parasitic emission
- **New hardware**
  - Power and polarization monitor
  - FPGA controls
  - Helium reliquifier
- **System upgrade**
  - 1.2 MW gyrotron
  - Addition to gyrotron vault
  - Waveguide rerouting
- **Long term plans**
- **Summary**

Performance and reliability

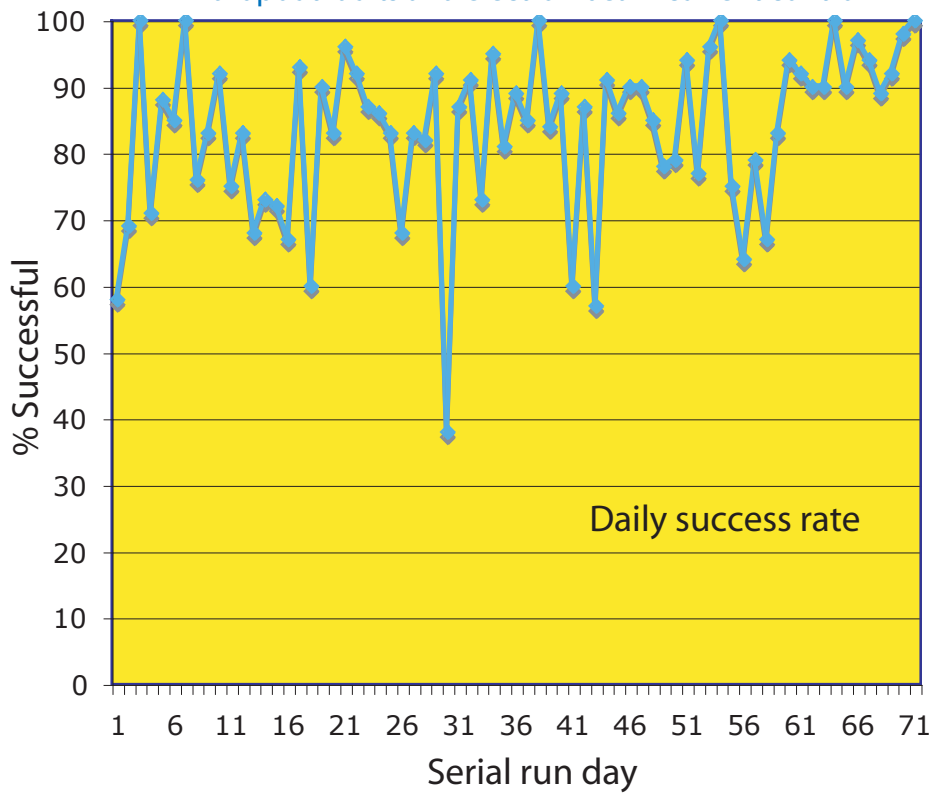
Overall ECH system reliability in campaign year 2010 84%

Max injected power 3.5 MW
Max injected energy single plasma shot 16.6 MJ
Max gyrotron pulse length 5.0 sec (administrative)

71 experimental days requesting gyrotrons
20-Oct-2009 through 6-Apr-2-10
5617 requests for individual gyrotrons
4707 successes



Most problems were related to power supply regulation, RF dropout faults and electron beam current control

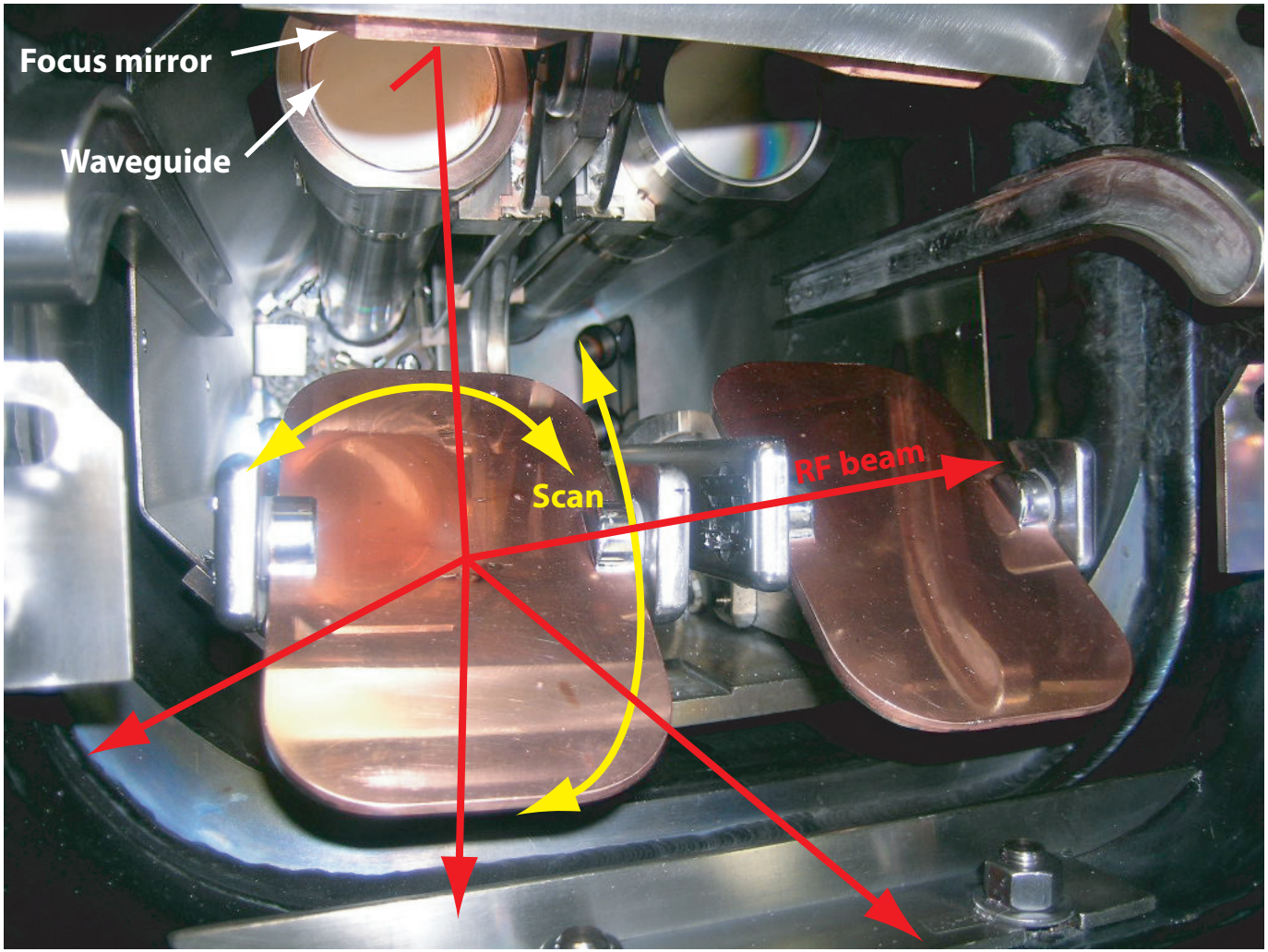


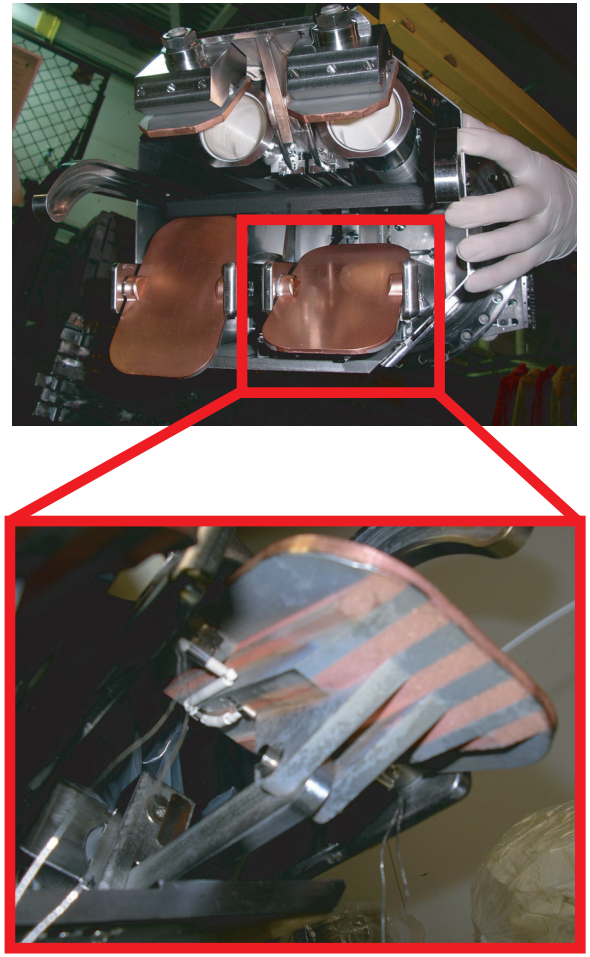
Outline

- **Gyrotron system description**
- **Performance data for the 2009-2010 campaign**
- **Selected physics experiments featuring ECH**
  - NTM suppression with real time poloidal steering control
  - Modulated temperature gradient transport study
  - Startup
- **Gyrotron system related experiments and techniques**
  - Optical spectrometer measurements
  - Using DIII-D bolometers to measure injected power
  - RF/waveguide alignment
  - Low frequency parasitic emission
- **New hardware**
  - Power and polarization monitor
  - FPGA controls
  - Helium reliquifier
- **System upgrade**
  - 1.2 MW gyrotron
  - Addition to gyrotron vault
  - Waveguide rerouting
- **Long term plans**
- **Summary**

DIII-D ECH launchers

The mirrors are not actively cooled and are rated for 1.0 MW, 5.0 sec pulses
Scan range is ±20° both poloidally and toroidally



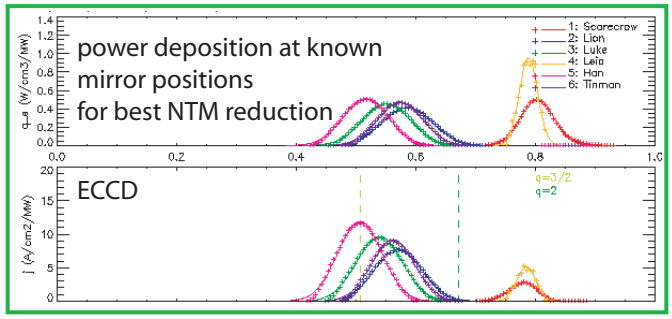


Flat steering mirror

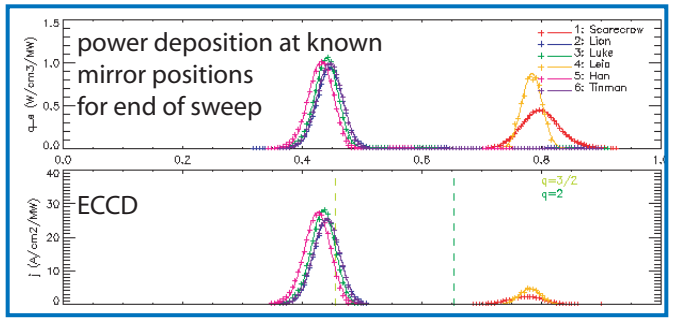
Reduction of the m/n=3/2 NTM with ECCD poloidal scan

The new electric motor drives for quasi-poloidal scanning of the ECH rf beams have been demonstrated to permit the reduction of the amplitude of the m/n=3/2 NTM in the first proof of principle experiment of this new capability at DIII-D.

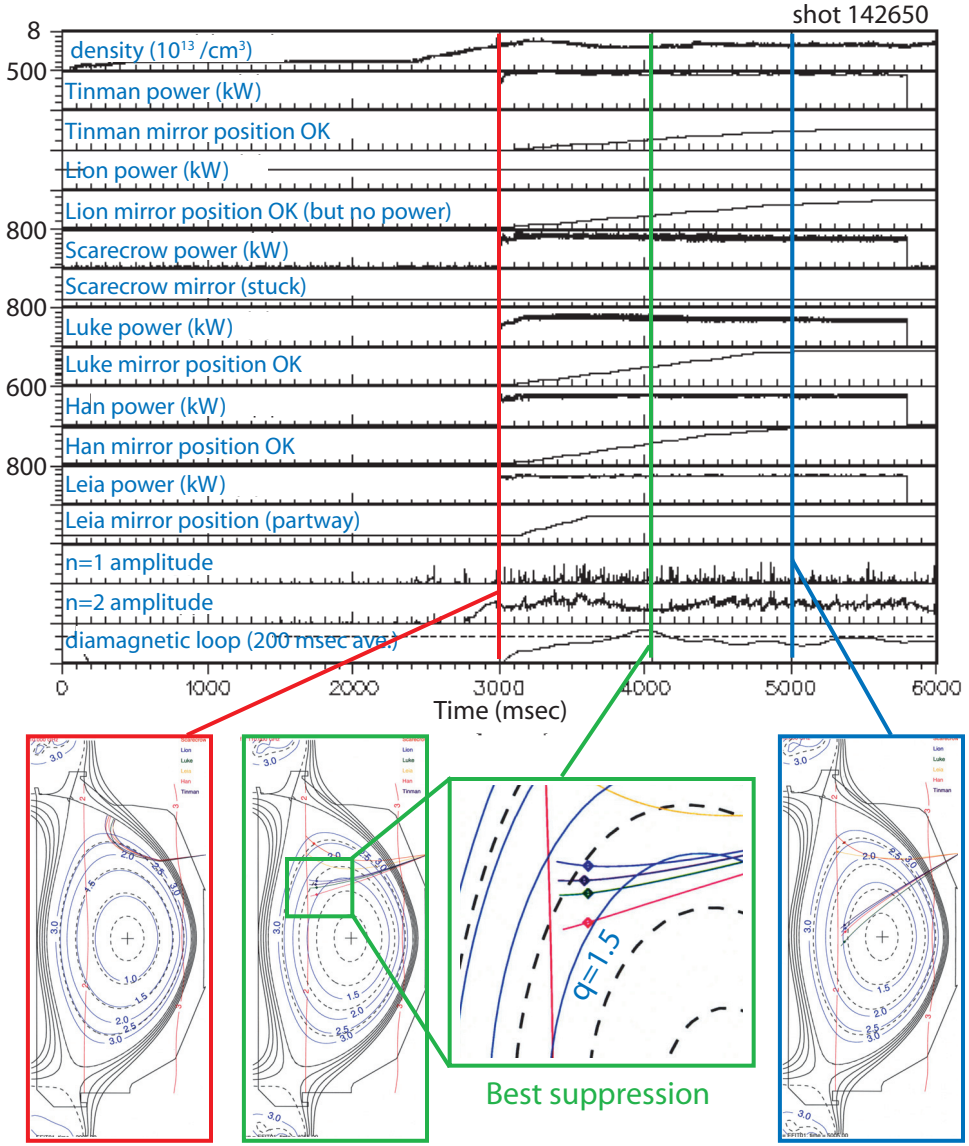
- Poloidal scan ~12°/sec, full 40° scan in 3.4 sec
- PCS control with a step function move command
- For this scan, Lion mirror scanned, but was not powered
- The Leia mirror moved about 20% of the command and stopped
- The Scarecrow mirror did not move due to a mechanical problem
- Three mirrors moved correctly and their gyrotrons injected ~1.5 MW ECCD
- Mechanical and control issues need to be addressed
- PCS feedback algorithms will be developed
- Mirror positions will be added to MDS



4050 msec
during NTM reduction
Deposition was broad
because of the different
sweep speeds for the
four moving mirrors

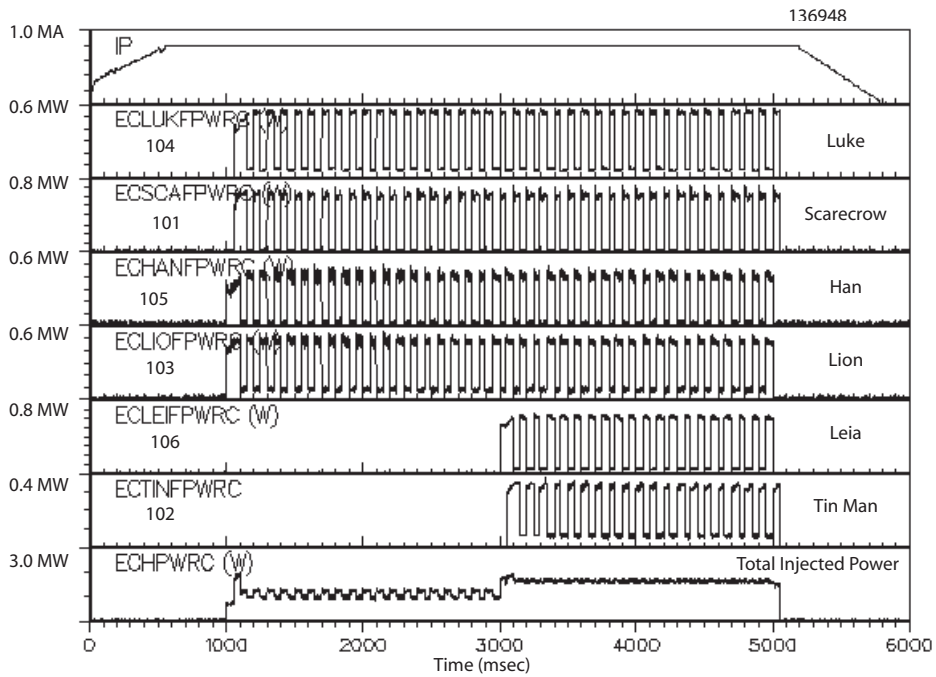


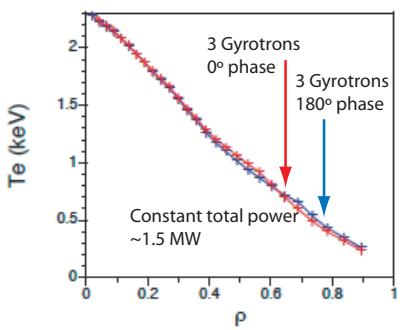
5000 msec
at the end of the
scan motion

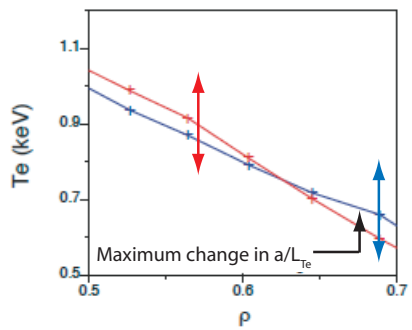


DIII-D NATIONAL FUSION FACILITY

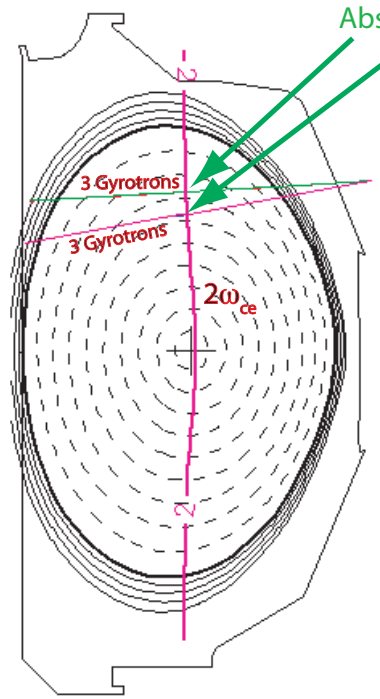
Turbulent transport experiment with modulated gyrotrons



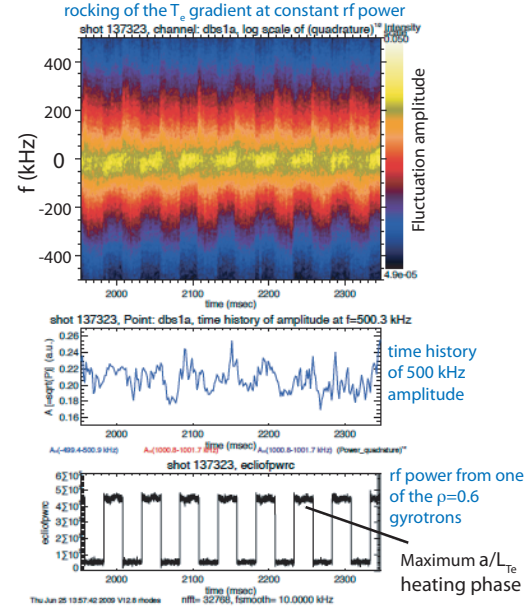




- ECH heating at ρ=0.6 and 0.7
- Total injected power constant
- Injection 180° out of phase at two locations
- Rock the T_e gradient periodically
- Use time correlation analysis



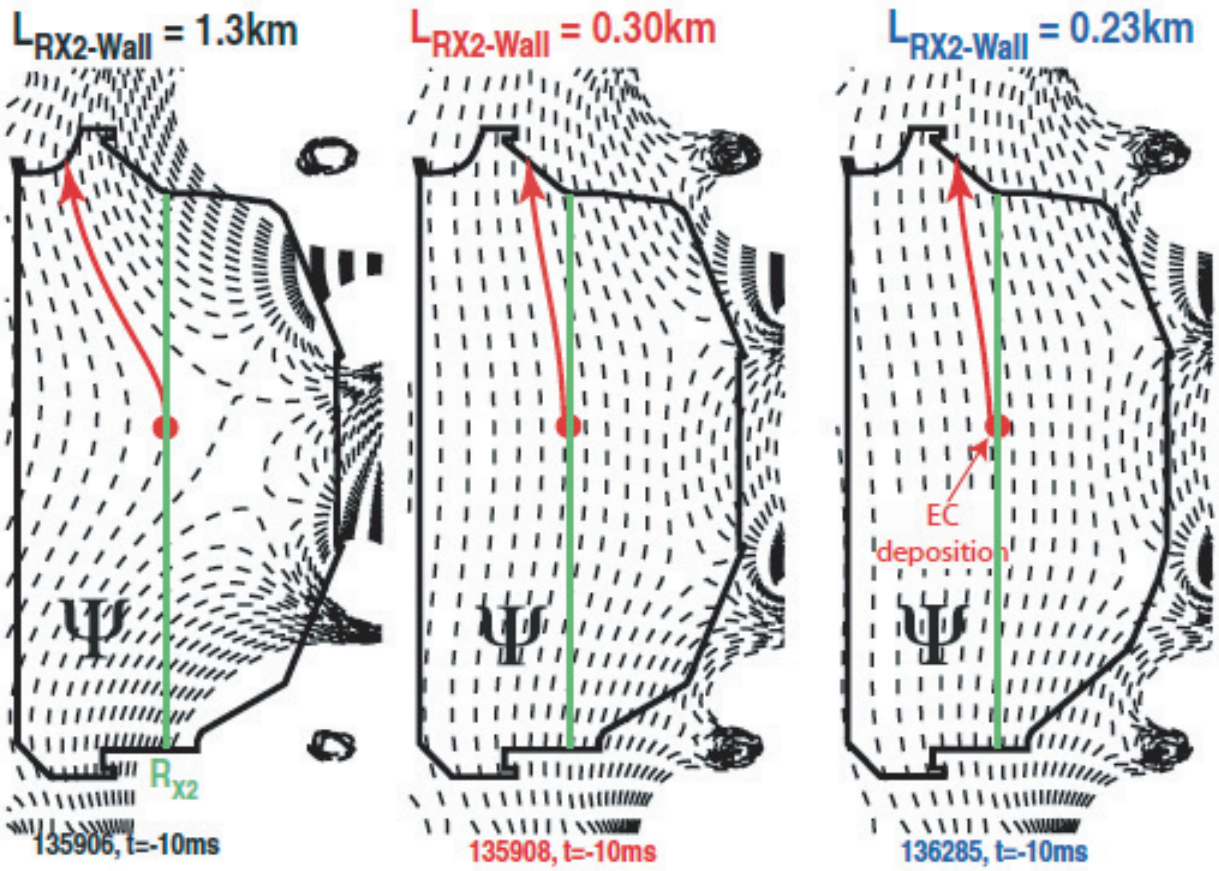
Doppler backscatter spectrum during periodic rocking of the T_e gradient at constant rf power

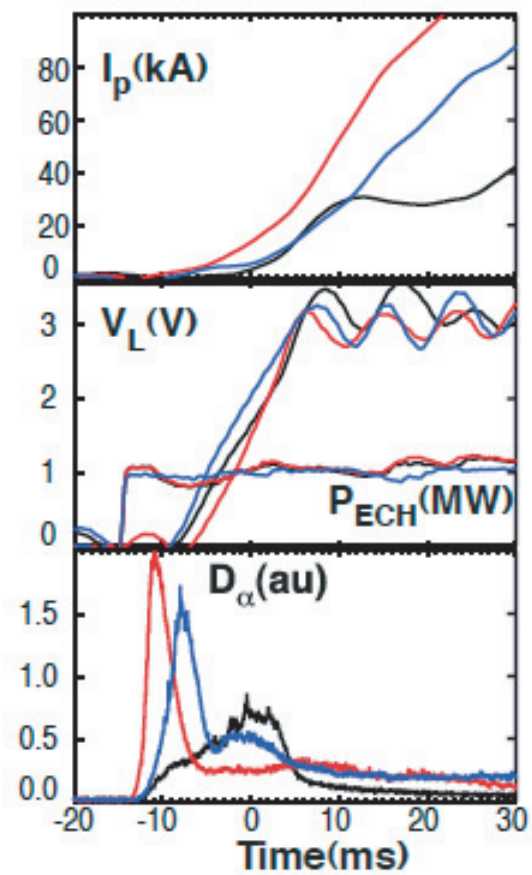


Fluctuation amplitude increases and frequency decreases during the period of steeper gradients

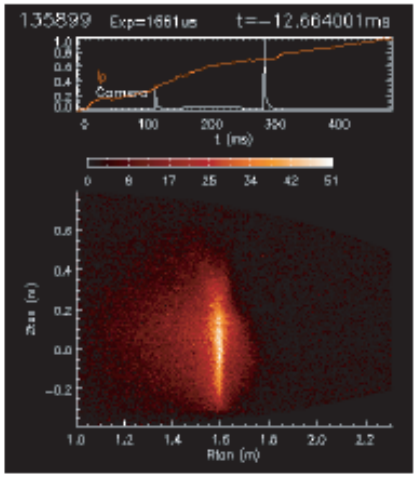
ECH startup

- ECH startup is prompt
- Best startup occurs when flux is nearly aligned with the EC resonance surface

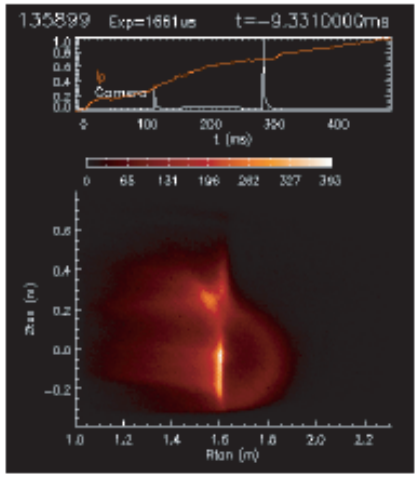




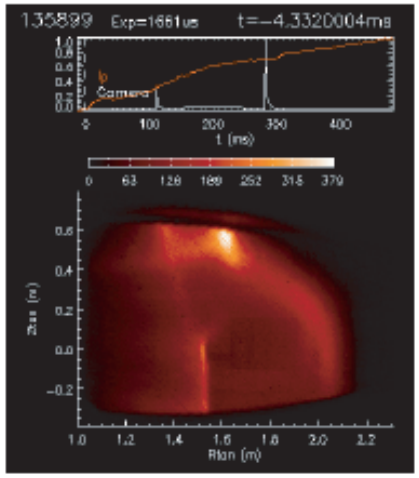
ECH startup seen by fast camera in C^{III} light



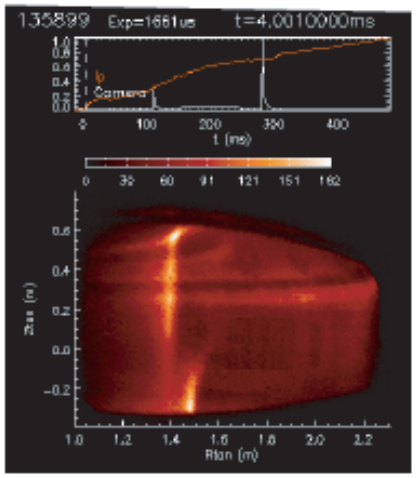
t= -12.7 ms, I p =1.8 kA, V_L= 0V
(Breakdown near X2 resonance)



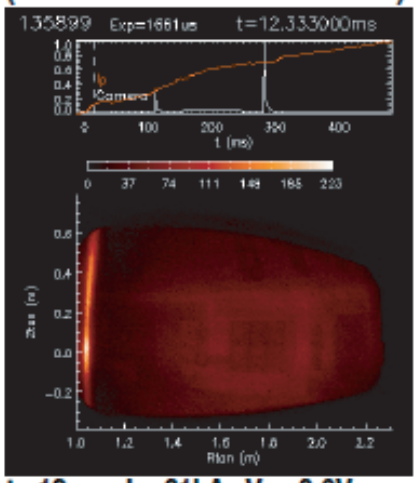
t= -9,3 ms, I p =1.9 kA, V_L= 0V
(CIII Light expands)



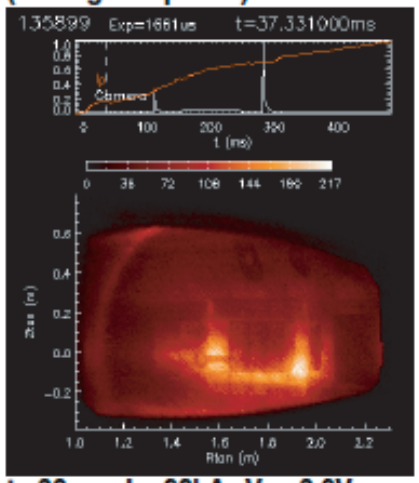
t= -4.3 ms, I p =5.6 kA, V_L= 0.6V
(Further expansion with V_L)



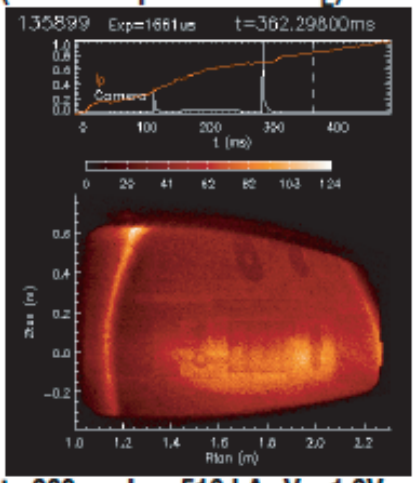
t= +4.0ms, I p =25kA, V_L=2.6V
(Closed flux, starts inward)



t= 12 ms, I p 61kA, V_L= 3.0V
(Limits on Inner Wall)



t= 39 ms, I p 98kA, V_L= 3.0V
(Limits on Outer Wall)



t= 360ms, I p =510 kA, V_L=1.3V
(Diverted)

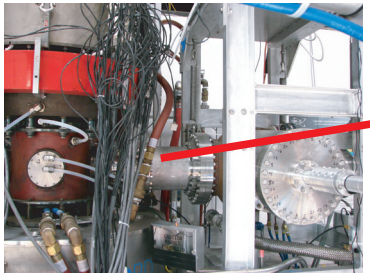
R_{IW}(midplane) = 1.02 m
R_{X2} = 1.64 m
R_{OW}(midplane)=2.36m
B_ϕ=1.9T, V_L=3V, $B_{V,pgm}$=-30G
$C^{III}_{ionization}$ = 48 eV
$C^{III}_{burnthrough}$ ≈ 16-24 eV

Outline

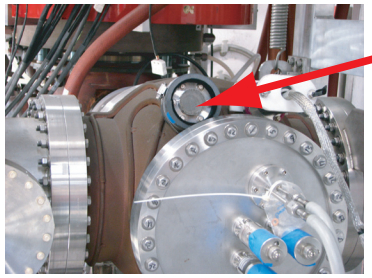
- **Gyrotron system description**
- **Performance data for the 2009-2010 campaign**
- **Selected physics experiments featuring ECH**
  - NTM suppression with real time poloidal steering control
  - Modulated temperature gradient transport study
  - Startup
- **Gyrotron system related experiments and techniques**
  - Optical spectrometer measurements
  - Using DIII-D bolometers to measure injected power
  - RF/waveguide alignment
  - Low frequency parasitic emission
- **New hardware**
  - Power and polarization monitor
  - FPGA controls
  - Helium reliquifier
- **System upgrade**
  - 1.2 MW gyrotron
  - Addition to gyrotron vault
  - Waveguide rerouting
- **Long term plans**
- **Summary**

Spectrum of light exiting a gyrotron

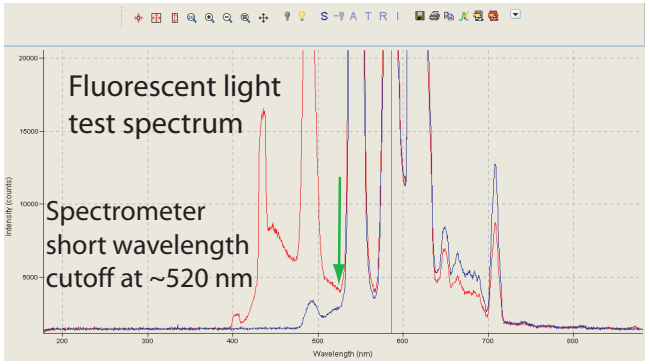
The object is to understand the sources of light exiting through the gyrotron diamond window during a fault while conditioning



Ocean Optics spectrometer viewing sightline above L-Box mirror and through gyrotron diamond output window

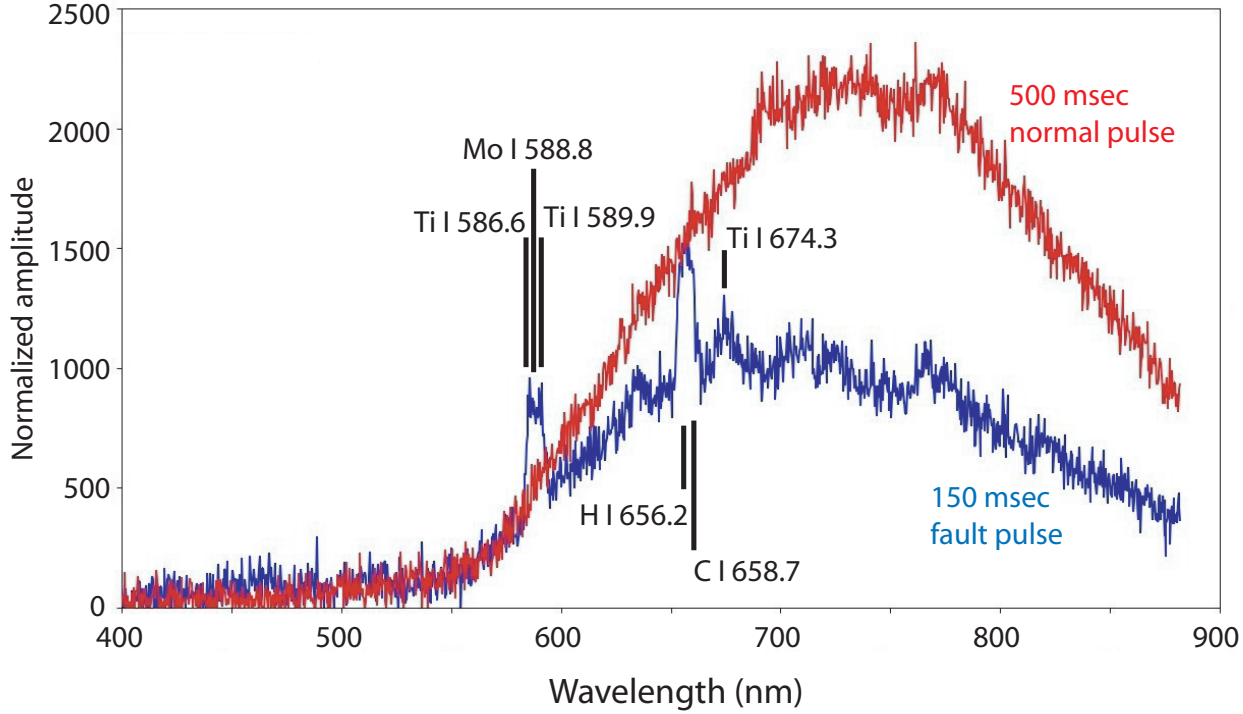


Sapphire viewport



Spectral response check

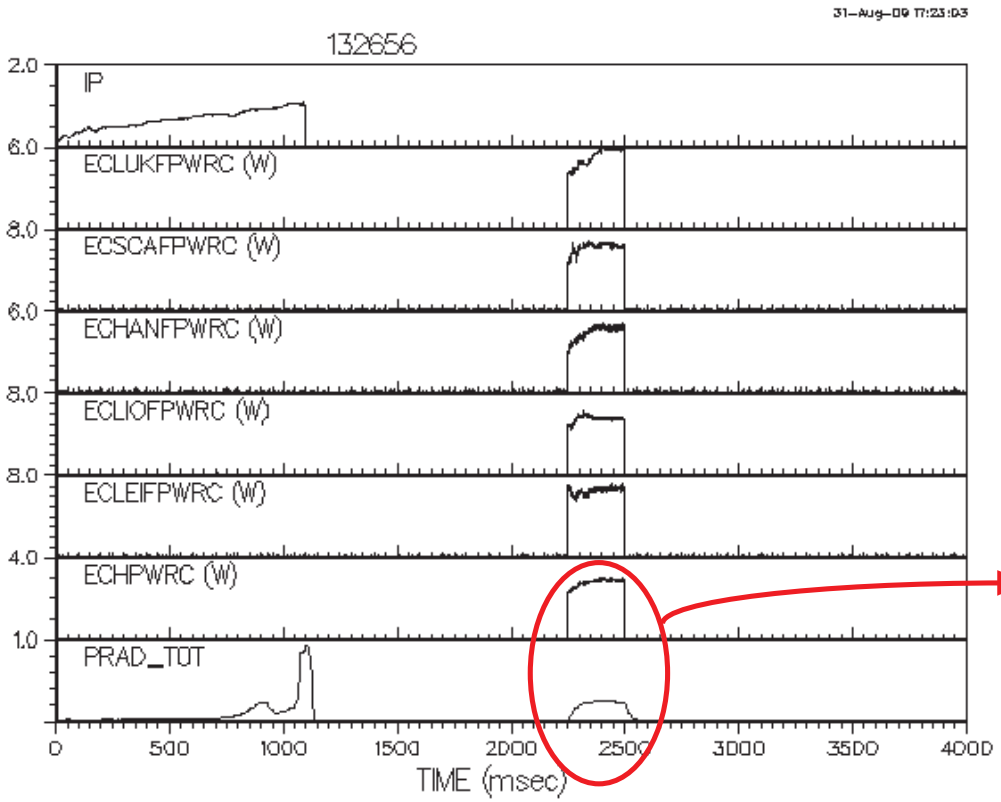
Hydrogen from inside the gyrotron
Titanium in the gyrotron vacion but TiO_2 also coats the MOU



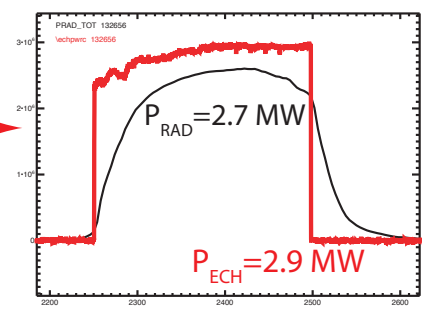
We will next try this with a high resolution spectrometer normally used for spectroscopic work on DIII-D
Does the vacion arc and regurgitate gas on especially bad shots?

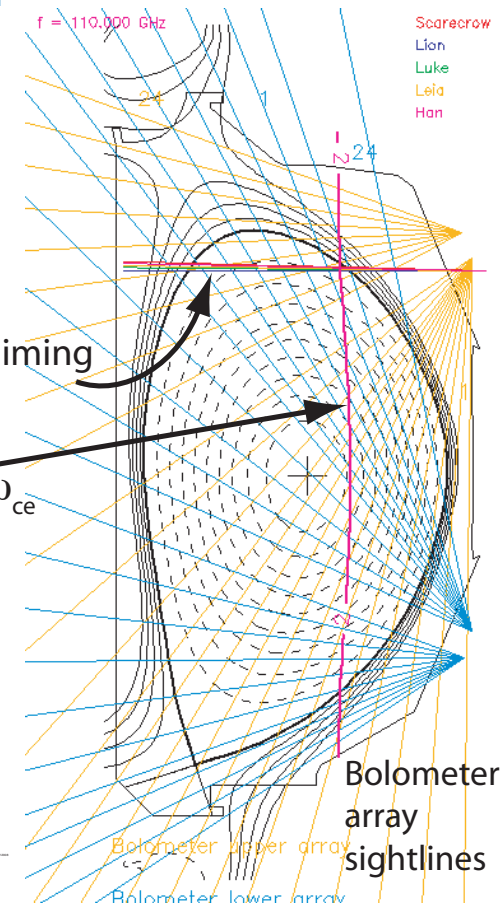
Radiated power due only to ECH with B_T and gas

On an ELM control experiment the plasma disrupted and ECH fired later because the requested pulse length was only 250 msec, the maximum allowed into the empty vessel so the I_P interlock was not active.



The RF generated a discharge and the bolometer array calculated total radiated power close to the calibrated value



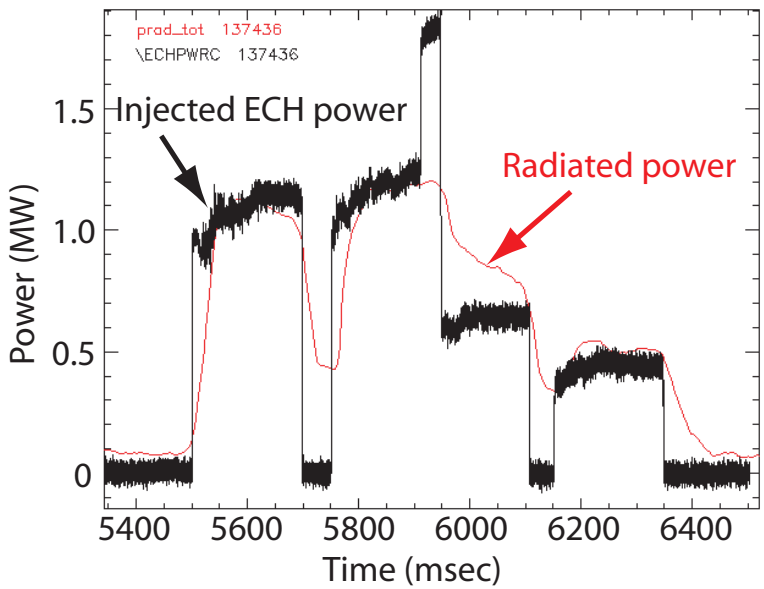


This suggested that the radiated power could provide an injected power calibration check

Injected power measurement using DIII-D bolometers

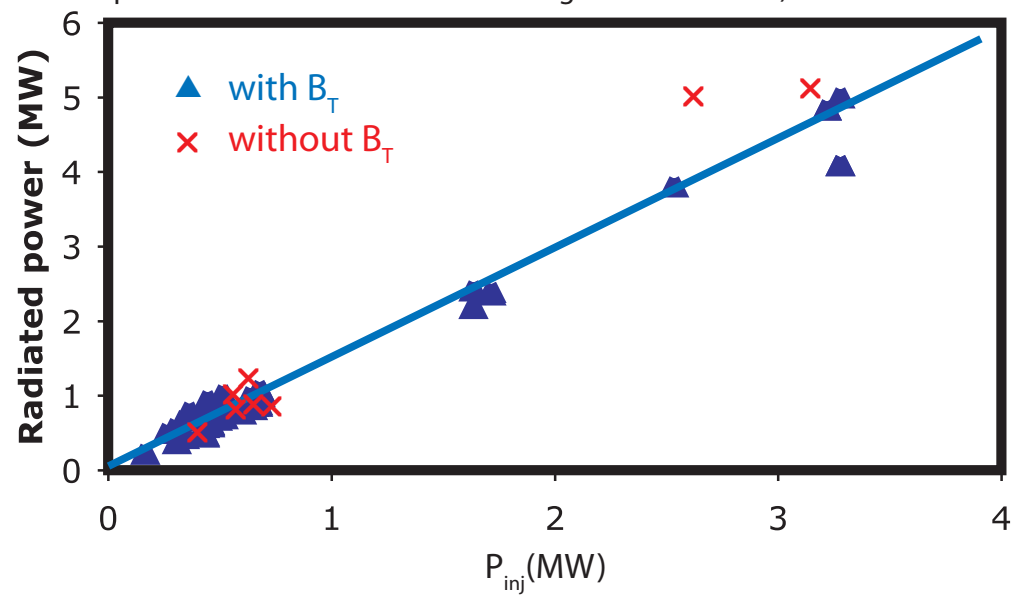
Specialized tomographic analysis may be required for this calibration technique

Radiated power and injected power from ECH calibration data compared for one example of rf aiming which happens to give good agreement



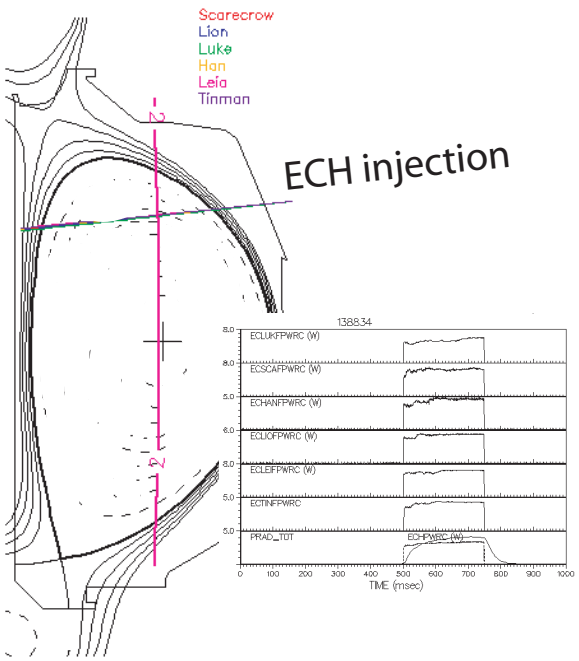
Linearity demonstration

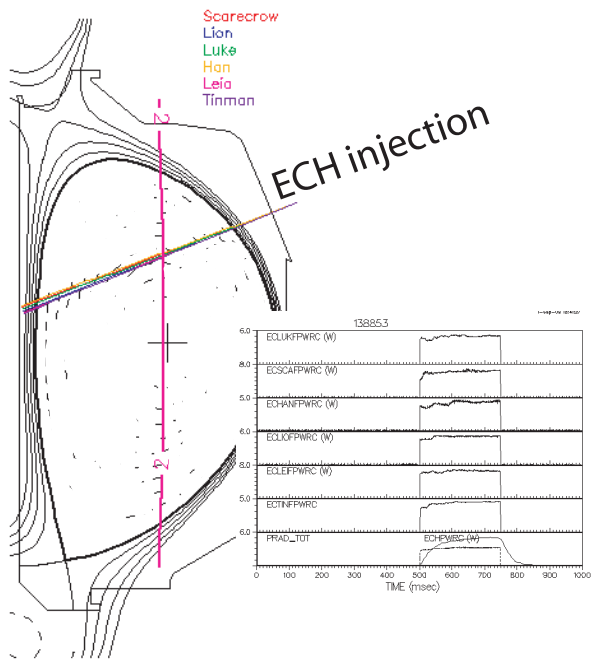
The calibration proportionality constant depends weakly on presence of a resonance but the main effect is the aiming of the rf beam (see plot on the left for a different aiming than these data).

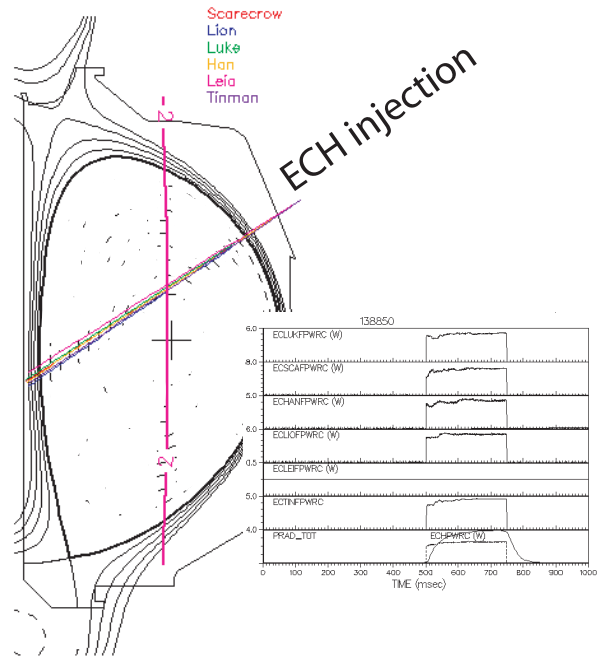


Dependence of bolometer response is always linear, but the scale factor depends on how the rf is aimed and whether there is a resonance in the vessel or not due to the tomographic analysis folded into the presentation of the bolometer total power signal.

Poloidal injection angle scan for P_{rad}/P_{inj}







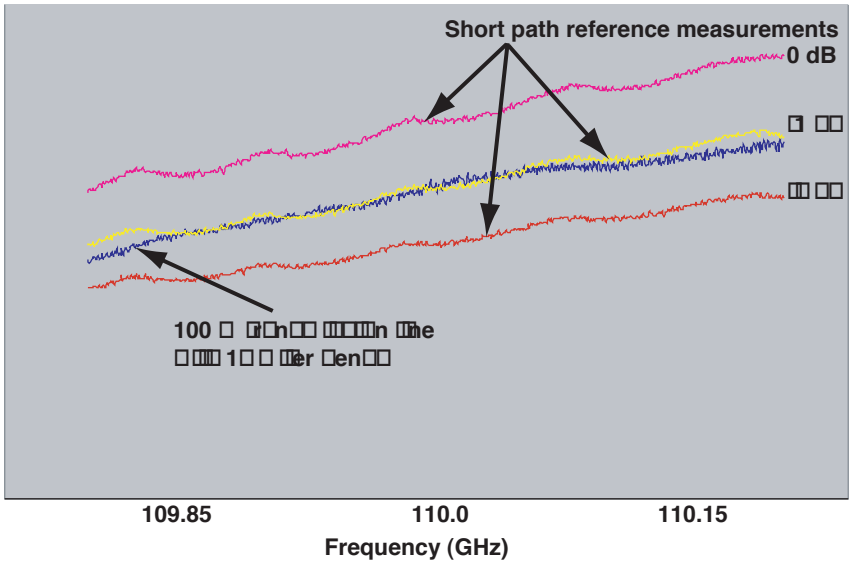
P_{rad}/Pinj=1.23 P_{rad}/Pinj=1.56 P_{rad}/Pinj=1.53

- In general the bolometric radiated power measurement overestimates the injected rf power
- Somewhat sensitive to injection geometry, especially at the edge of the normal plasma volume
- Very reproducible for a given set of gas and B_T parameters
- Probably can get a tomographic analysis for bolometers that gives good agreement
- Does not work well with low prefill gas density
- Does work with no B_T if breakdown is robust
- Best agreement for high injection as happened by accident in the very first observation

Transmission line efficiency

Measurements of the transmission line efficiencies in hot test compared with cold test show hot test efficiency is generally lower than either predicted or measured in hot test

The suspicion falls on mode conversion at the beginning of the transmission line due to poor alignment



Cold test measurements using standard transmission line 31.75 mm dia and a carefully filtered $HE_{1,1}$ rf test signal

Expected losses 100 m 14 miter bends 31.75 mm dia aluminum w/g 110 GHz:

Mode conversion loss -.06 dB (1.4%) per miter for simple miters
loss for 14 miters -0.84 dB (82.4%)

Ohmic loss -0.003 dB per miter for copper H-plane reflection (0.0625%) per miter
loss for14 miters -.042 dB (1%)

Ohmic loss for 100 m of 31.75 mm dia aluminum waveguide at 110 GHz -0.21dB (5%)

Total expected efficiency for 100 m 14 miter line -1.09 dB (78 %)

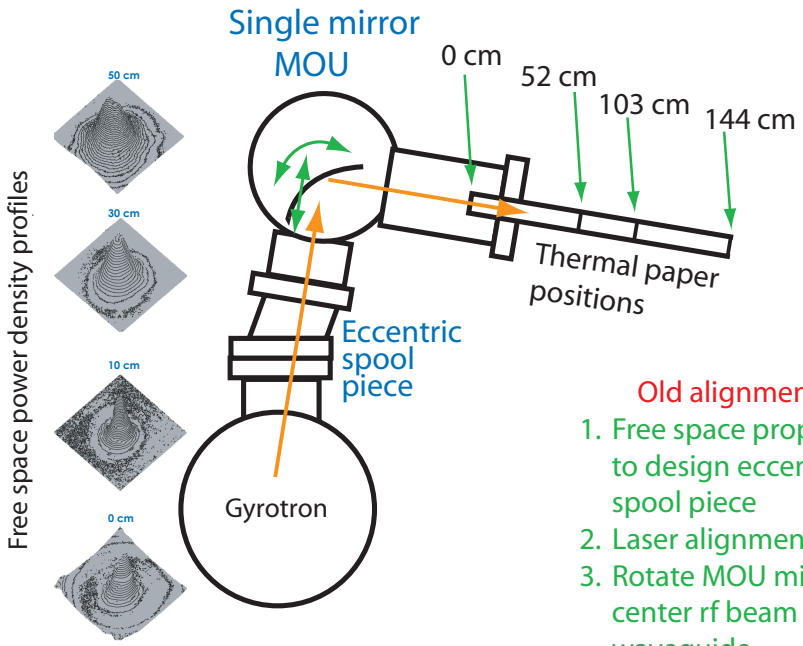
The theoretical performance was measured in cold test and for one hot test case

Other waveguides have between 5% and 10% additional loss in hot tests and waveguide heating near the injection point consistent with the additional loss is observed.

Comparison measurements with a CCR dummy load both at the gyrotron and near DIII-D coupled with the improved alignment technique are being done with the expectation that all the lines can be brought to the performance of the best one.

Improved alignment method

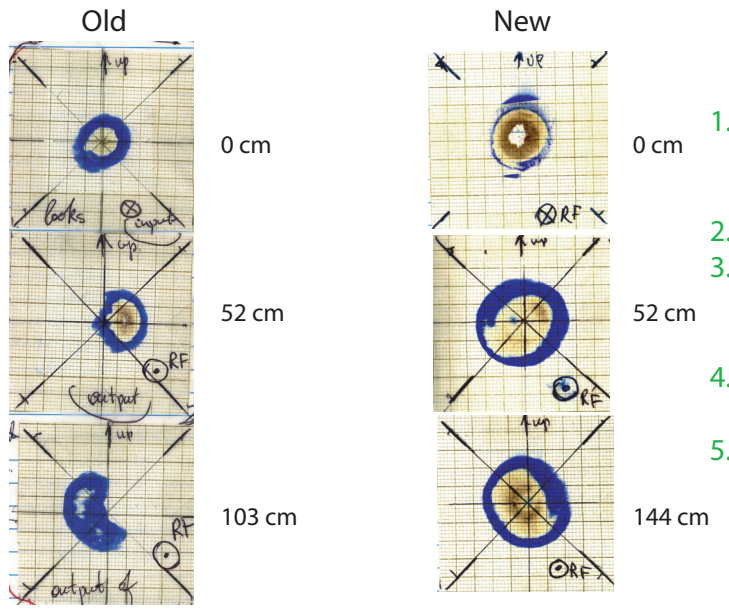
- Cannot easily determine tilt at injection point except by looking at points along the waveguide
- Transverse alignment accuracy is better than 1 mm
- One mirror MOU limits flexibility, particularly in the vertical plane
- Eccentric spool piece should put rf beam on optical axis but may not do this perfectly
- Should be able to couple 98% to $HE_{1,1}$ but using old technique we lost 5% or more due to misalignment in tilt
- Now achieve acceptable alignment with predicted losses of about -1 dB for the full line
- All lines now being aligned



Old alignment:

1. Free space propagation to design eccentric spool piece
2. Laser alignment
3. Rotate MOU mirror to center rf beam at waveguide

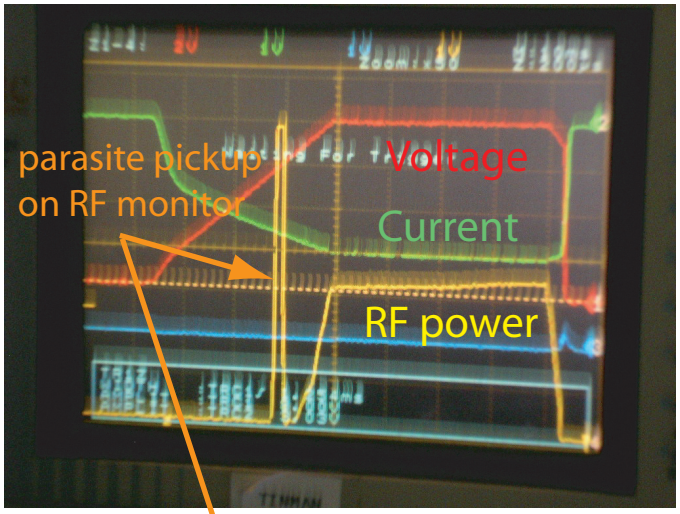
The new alignment technique has given one waveguide line with theoretical low loss performance and low waveguide heating in the first several meters of the transmission line.



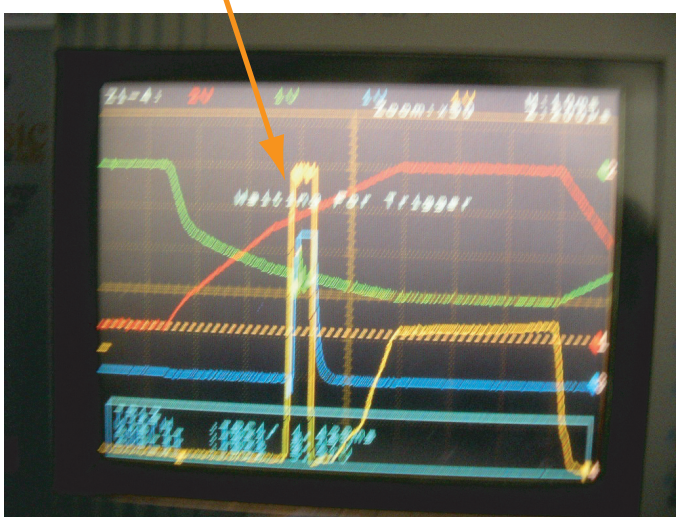
New alignment:

1. Free space propagation to design eccentric spool piece
2. Laser alignment
3. Propagate rf beam into free space to set angle and x-y
4. Install waveguide along rf beam line
5. tilt mirror to make final alignment in x-y position

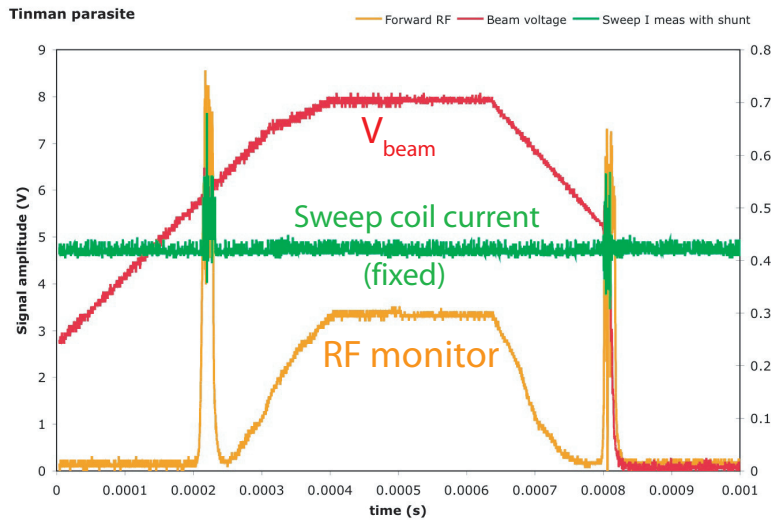
Parasite depending on collector sweep and beam energy

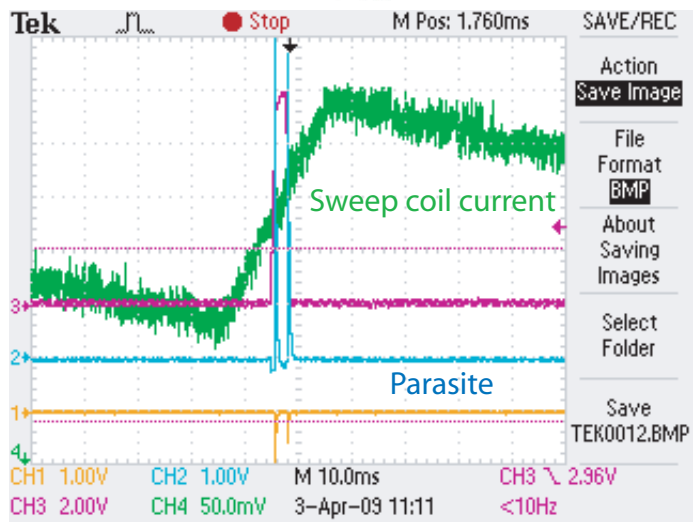


Faster ramp rate short parasite on-time



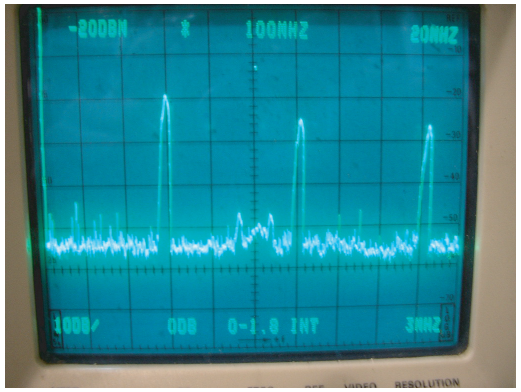
Slower ramp rate longer parasite on-time





Requires specific sweep coil current and beam energy

- Parasite sensitive to B_u value
- Disappears when low vacion current (clean gyrotron)
- Can be at other than 60 MHz
- Only occurs at certain middle values of sweep coil current when beam is in the middle of the collector
- Occurs during voltage ramp down and ramp up
- Parasite on-time increases when voltage ramp is slowed
- Parasite is present for V_b=58~60 kV



60 MHz parasite plus harmonics

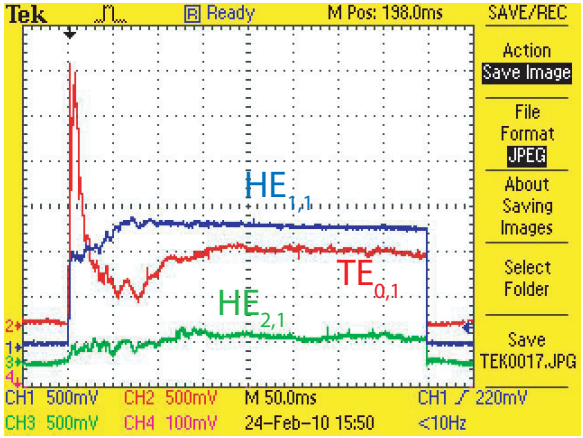
Outline

- **Gyrotron system description**
- **Performance data for the 2009-2010 campaign**
- **Selected physics experiments featuring ECH**
  - NTM suppression with real time poloidal steering control
  - Modulated temperature gradient transport study
  - Startup
- **Gyrotron system related experiments and techniques**
  - Optical spectrometer measurements
  - Using DIII-D bolometers to measure injected power
  - RF/waveguide alignment
  - Low frequency parasitic emission
- **New hardware**
  - Power and polarization monitor
  - FPGA controls
  - Helium reliquifier
- **System upgrade**
  - 1.2 MW gyrotron
  - Addition to gyrotron vault
  - Waveguide rerouting
- **Long term plans**
- **Summary**

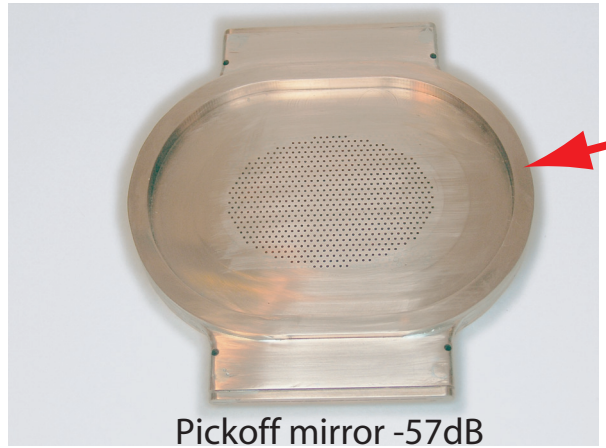
Power monitor miter bend

The monitor can measure both perpendicular polarizations using an orthomode transducer, or the $HE_{1,1}$ content and the content of interfering higher order modes, $TE_{0,1}$ and $HE_{2,1}$ using a mode sensitive directional coupler

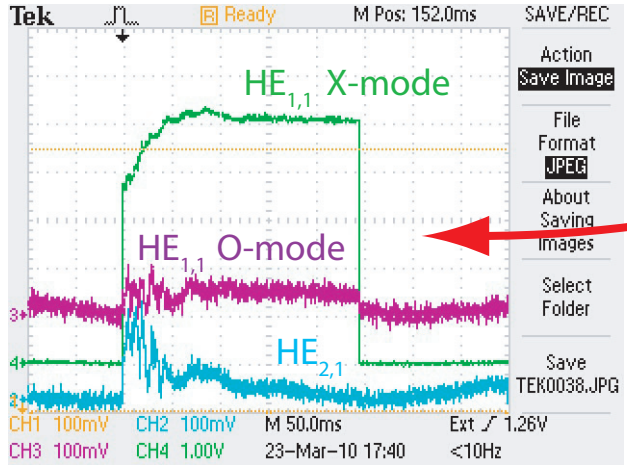
Miter in waveguide line with directional coupler installed for alignment checks and mode conversion measurements close to gyrotron



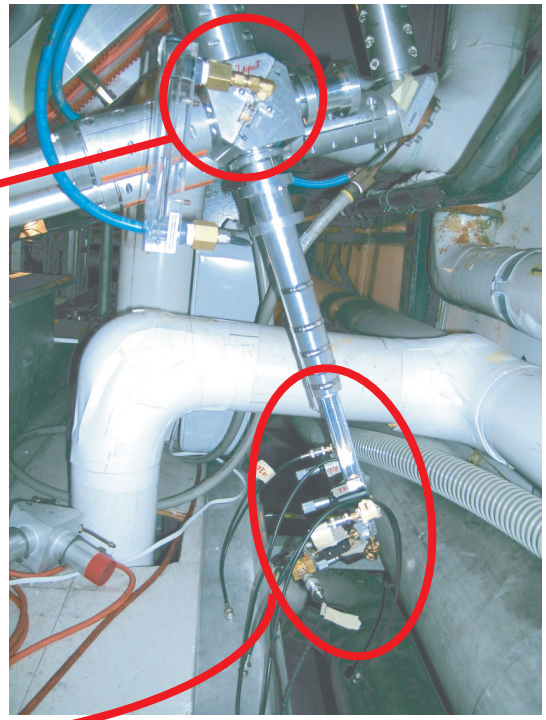
Alignment traces near gyrotron (a.u.)



Pickoff mirror -57dB



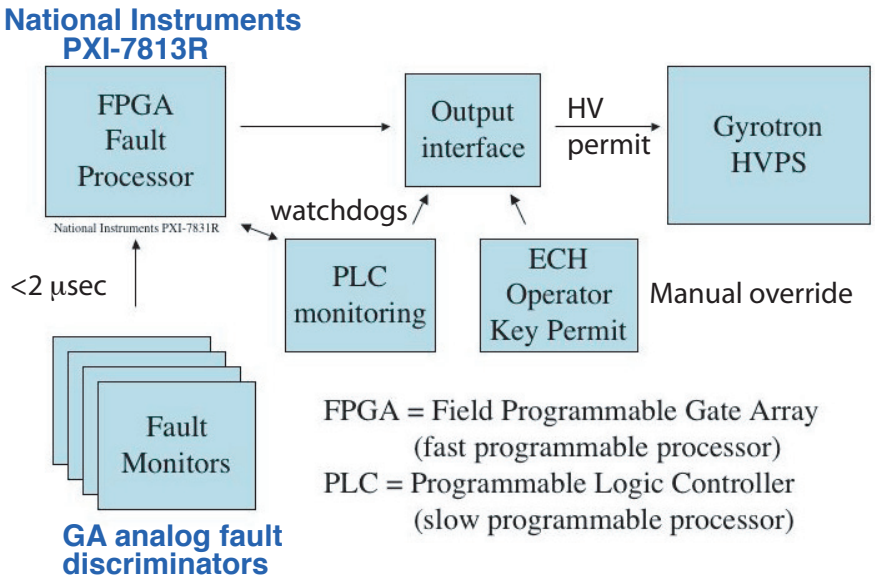
RF beam traces at last miter in pit using orthomode transducer for polarization



Power monitor miter installed in waveguide in the DIII-D machine pit for polarization checks and mode conversion measurements at the launcher end of the transmission line. A low pass filter stops 220 GHz second harmonic from being detected.

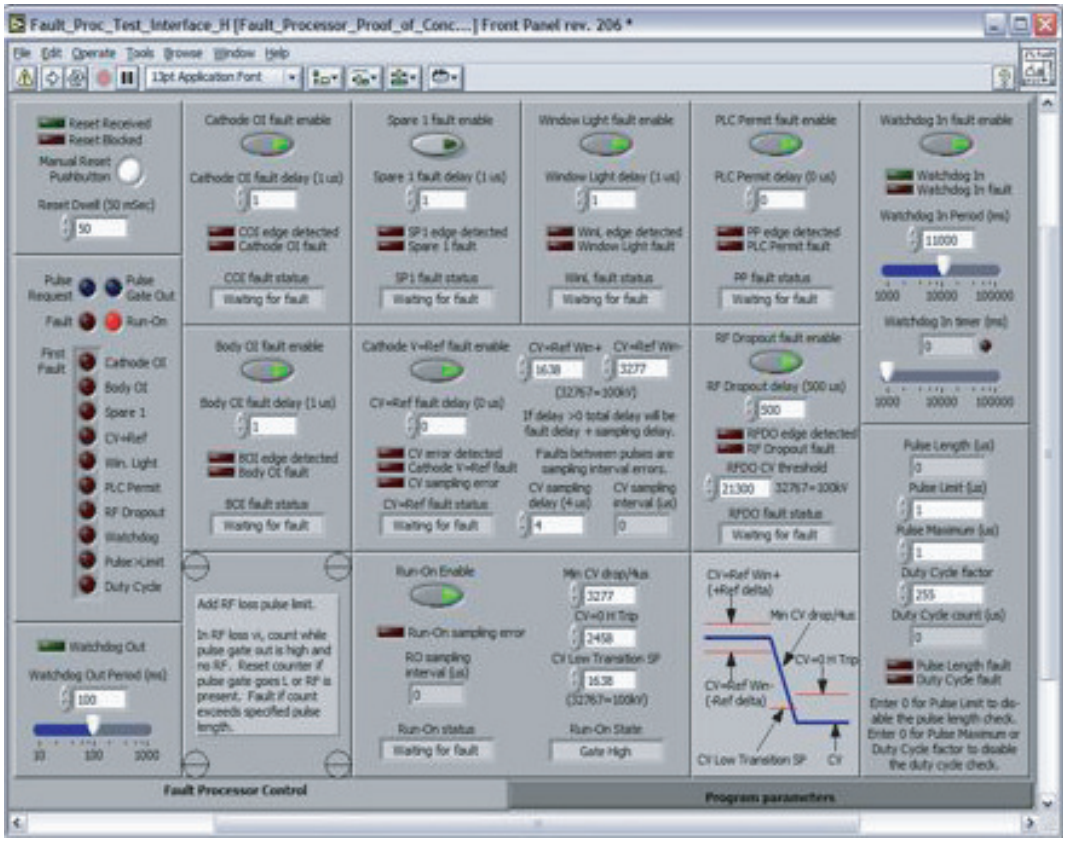
FPGA-based fault and control system

FPGA (Field Programmable Gate Array) fault processor system is replacing the discrete component fault processors for fast faults such as window arcs and cathode overcurrents. The system provides excellent speed, flexibility and reliability. The hardware was operated for over a year off line in a reliability test.



FPGA = Field Programmable Gate Array
(fast programmable processor)
PLC = Programmable Logic Controller
(slow programmable processor)

Detected faults remove the HV pulse permissive and the crowbar will then fire if the HV is not successfully blocked. Protection for the gyrotron is checked by shorting the HV power supply with a 26 gauge copper wire (0.41 mm dia), which must survive the test. This represents 10 J maximum energy deposited into a fault. First fault discrimination is possible for events separated by ≥ 40 nsec. An upgraded version under development will allow pre-fault conditions to be sensed and mitigated allowing the gyrotrons to restart without blocking and completely losing the shot.



Interface screen allows operators to set fault parameters

Helium reliquifier

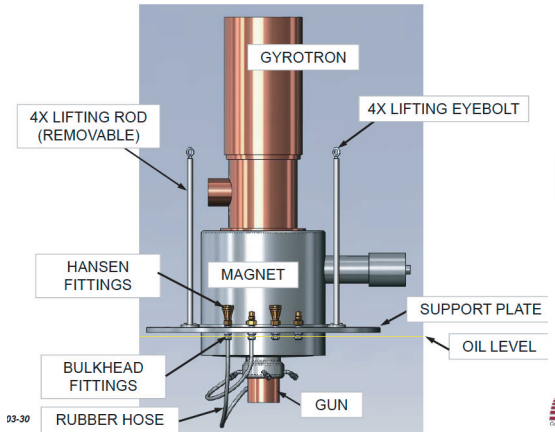
Cryomech pulse tube helium reliquifier

- Capacity >10 liters/day (far exceeds the requirement)
- Has a 2 W heater to maintain positive pressure of 0.2 psi
- 7.5 kW
- LHe loss rate ~0.1% per day
- Time between LHe fills ~ one year
- Time to full cost recovery ~2 years full time operation
- We are attempting to cross feed boiloff from another magnet to see if we can refill this one
- DIII-D has three cryogen-free magnets, two with cryogen- free radiation shields and this one with both LN_2 and LHe with the cryocooler
- Initial cost $91k

7th gyrotron upgrade

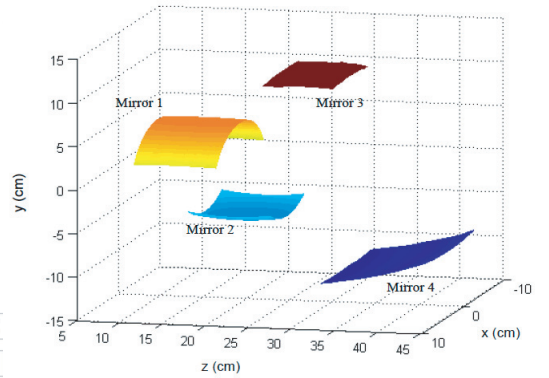
Prototype "Chewbacca"
was tested to 1.3 MW for short pulses

Collector will be larger than the prototype
OFHC collector and made from CuCrZr

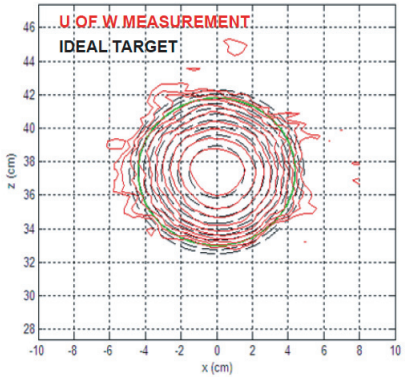


Concept

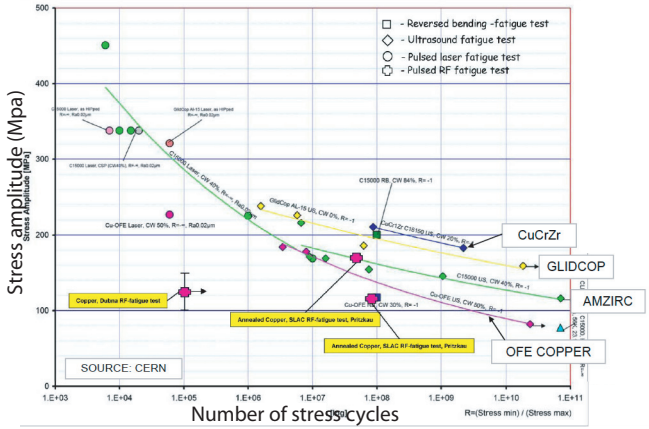
Four mirror rf relay designed using SURF3D by Jeff Neilsen



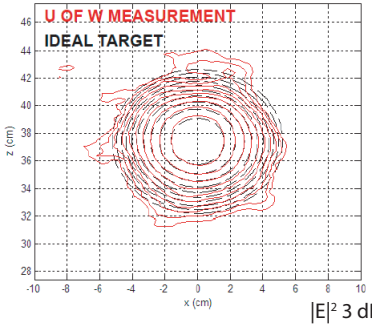
Window



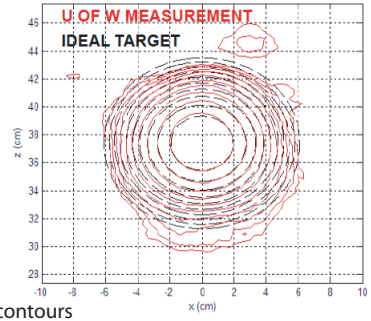
CuCrZr is slightly better than Glidcop and
both are about twice as good as OFCH Cu
(data from SLAC and others)



30 cm beyond window



60 cm beyond window



$|E|^2$ 3 dB contours

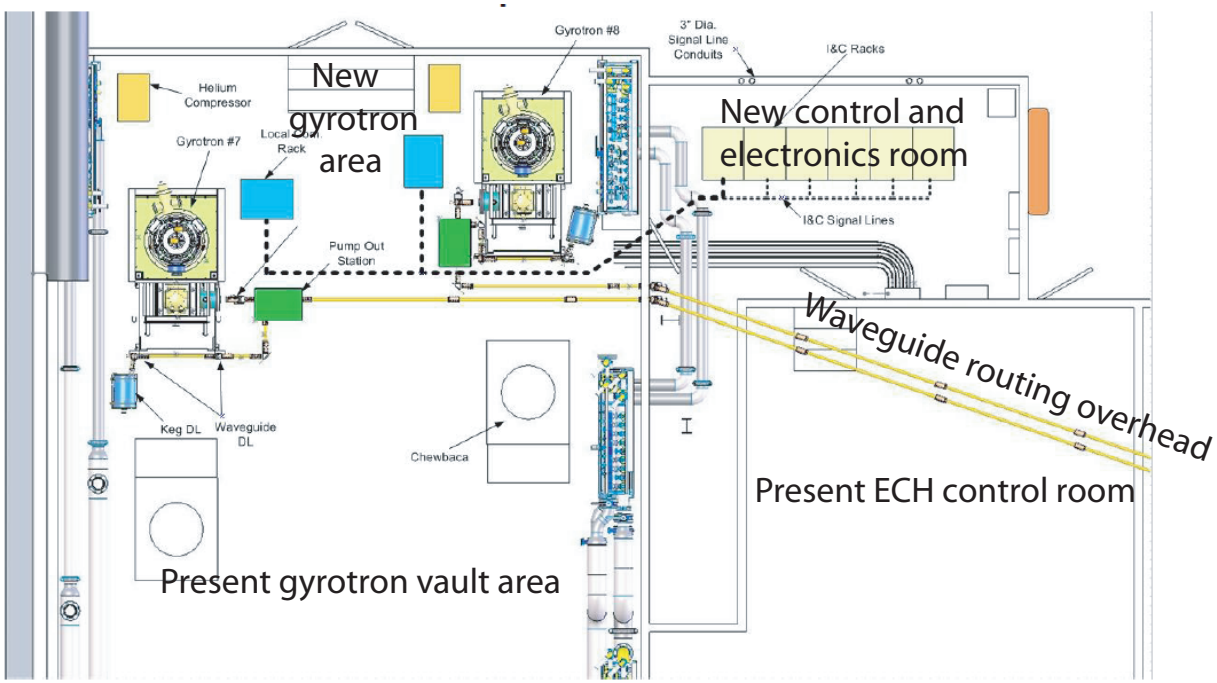
Cold tests of the prototype mirrors were performed at the University of Wisconsin

The depressed collector 110 GHz 7th gyrotron is
scheduled for factory tests in July 2011
Planned output power is 1.2 MW

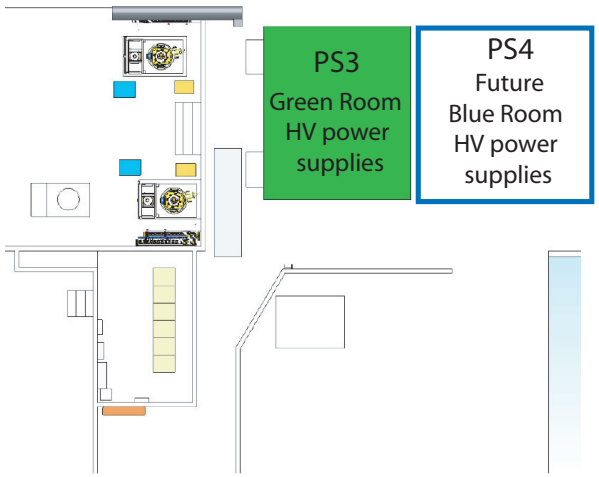
Expansion of the ECH system

We have a commitment for one new 1.3 MW depressed collector gyrotron, power supply, waveguide, launcher and controls and we are optimistically hoping for an additional 1.5 MW gyrotron

Layout detail for new gyrotron installation

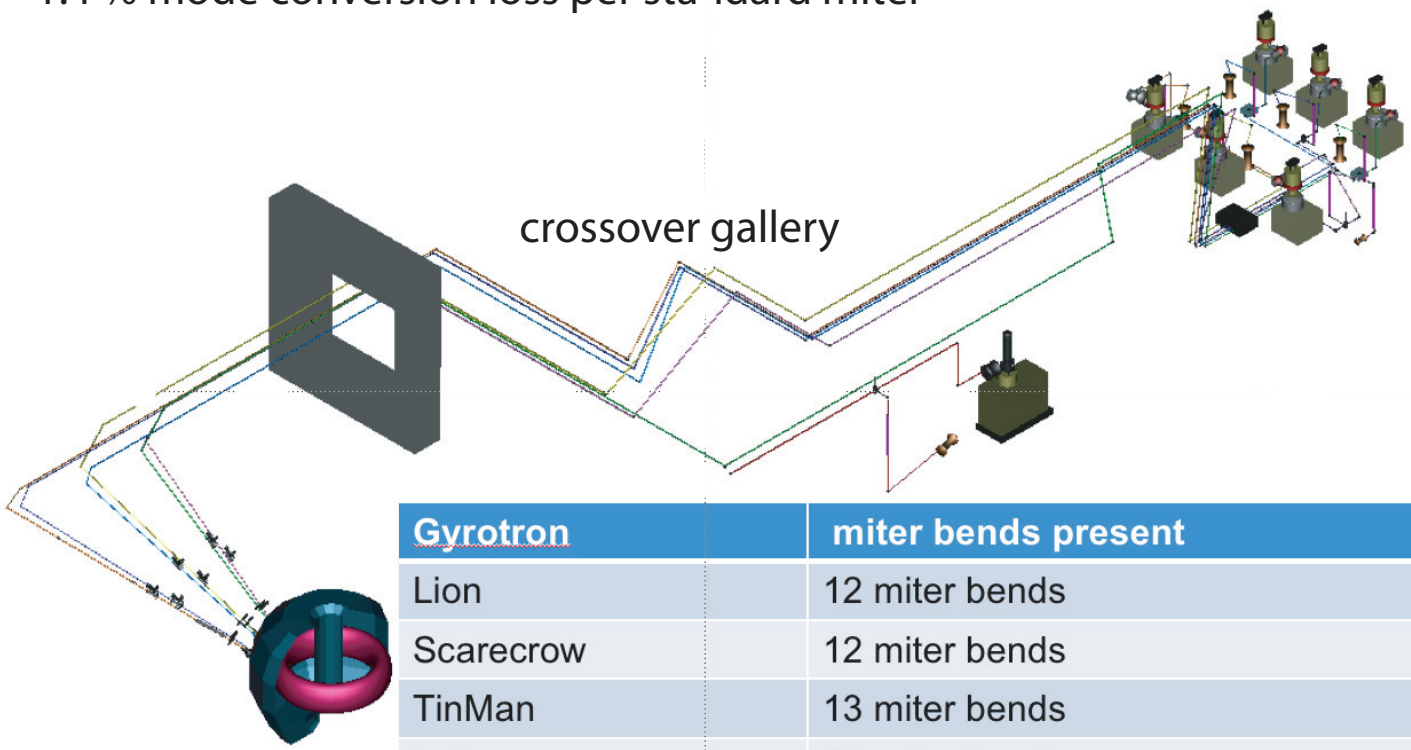


Power supply layout



Miter bend reduction

Present waveguide configuration
72 miter bends including polarizers
~1.4 % mode conversion loss per standard miter

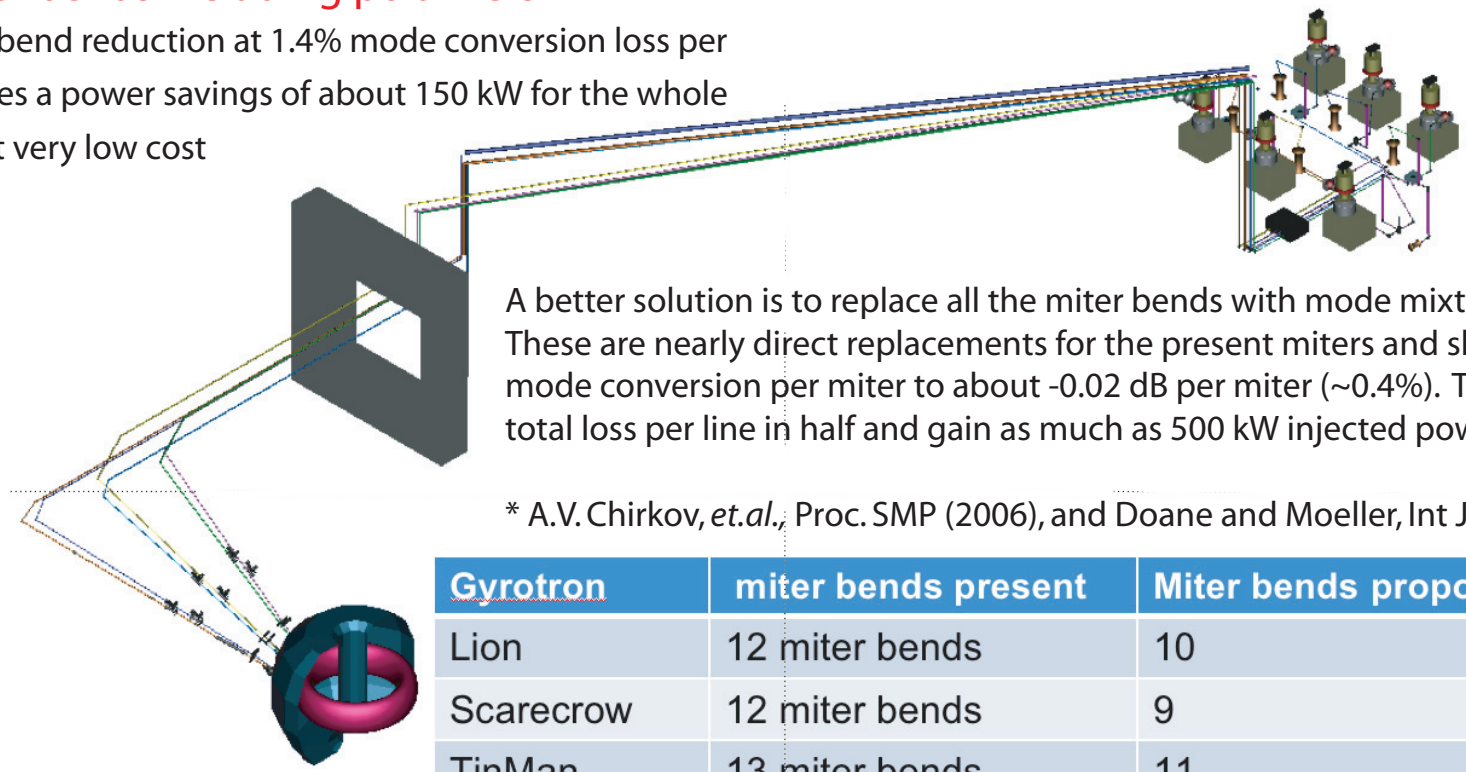


Gyrotron	miter bends present
Lion	12 miter bends
Scarecrow	12 miter bends
TinMan	13 miter bends
Leia	11 miter bends
Luke	12 miter bends
Han	12 miter bends

New waveguide runs

New waveguide routing
59 miter bends including polarizers

13 miter bend reduction at 1.4% mode conversion loss per miter gives a power savings of about 150 kW for the whole system at very low cost



A better solution is to replace all the miter bends with mode mixture miters*
These are nearly direct replacements for the present miters and should reduce the mode conversion per miter to about -0.02 dB per miter (~0.4%). This could cut the total loss per line in half and gain as much as 500 kW injected power for the system.

* A.V. Chirkov, *et.al.*, Proc. SMP (2006), and Doane and Moeller, Int J. Electronics, 77 (1994)

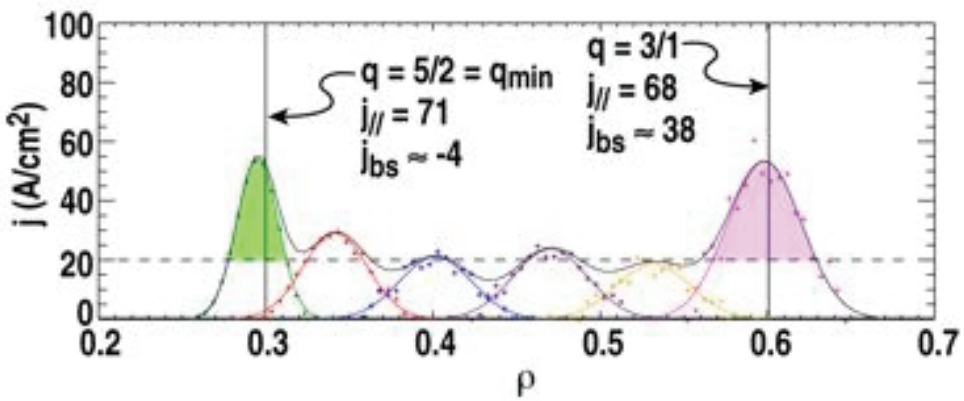
Gyrotron	miter bends present	Miter bends proposed
Lion	12 miter bends	10
Scarecrow	12 miter bends	9
TinMan	13 miter bends	11
Leia	11 miter bends	9
Luke	12 miter bends	10
Han	12 miter bends	10

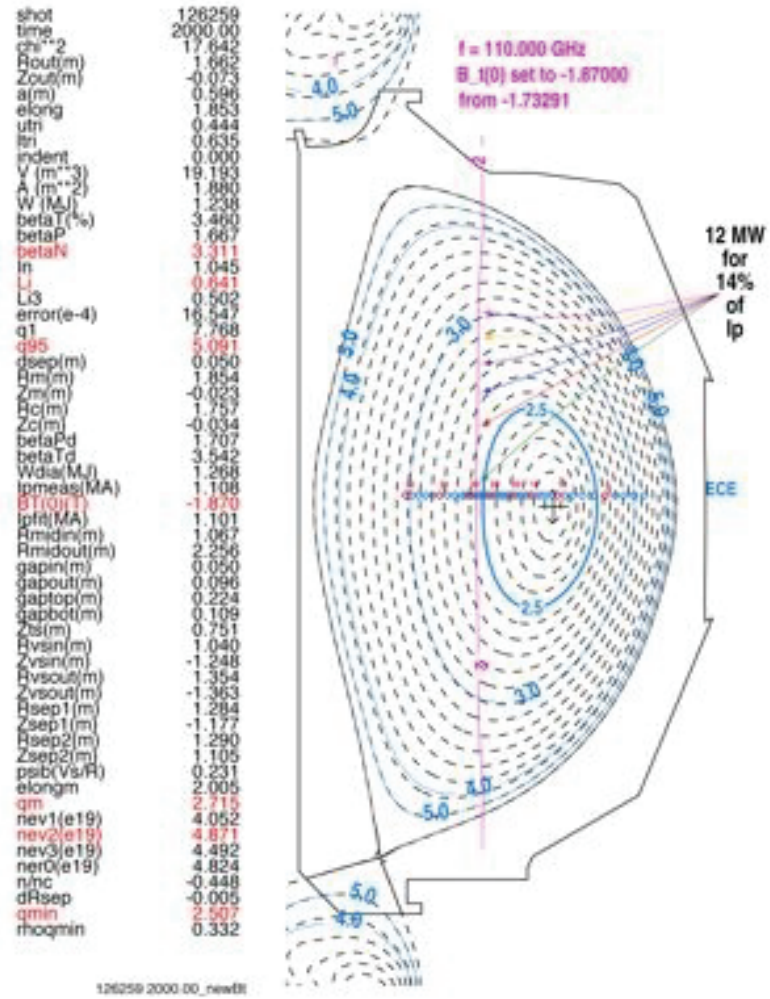
Outline

- **Gyrotron system description**
- **Performance data for the 2009-2010 campaign**
- **Selected physics experiments featuring ECH**
  - NTM suppression with real time poloidal steering control
  - Modulated temperature gradient transport study
  - Startup
- **Gyrotron system related experiments and techniques**
  - Optical spectrometer measurements
  - Using DIII-D bolometers to measure injected power
  - RF/waveguide alignment
  - Low frequency parasitic emission
- **New hardware**
  - Power and polarization monitor
  - FPGA controls
  - Helium reliquifier
- **System upgrade**
  - 1.2 MW gyrotron
  - Addition to gyrotron vault
  - Waveguide rerouting
- **Long term plans**
- **Summary**

DIII-D Needs ≈ 12 MW ECCD to Sustain High q_{min} Advanced Tokamak Discharges and Stably Preempt Tearing Mode

- **Sustainment requires broad ECCD**
  - ★ #126259 with 1.4 MW for ECCD 3% of I_p … not sustained ($V_{loop} \approx 0.1$ volts)
- **Tearing stability requires localized ECCD at q = m/n surfaces**
  - ★ $j_{eccd} \approx j_{bs}$ if NTM, $\approx \mathcal{O}(j_{//})$ if CTM
- **Shown below and right is 12 MW broad brush between q = 2.5 and 3**
  - ★ including localized ECCD





Summary

- DIII-D 6 gyrotron system in regular reliable service
- Injected power 3.3-3.5 MW
- Maximum injected energy 16.6 MJ
- Pulse lengths regularly are 5.0 sec, limited administratively to reduce tube fatigue
- Integration with Plasma Control System for modulation, mirrors, timing
- Upgrade to 7th depressed collector 1.2 MW gyrotron is funded
- Further upgrades to 12 MW are being proposed