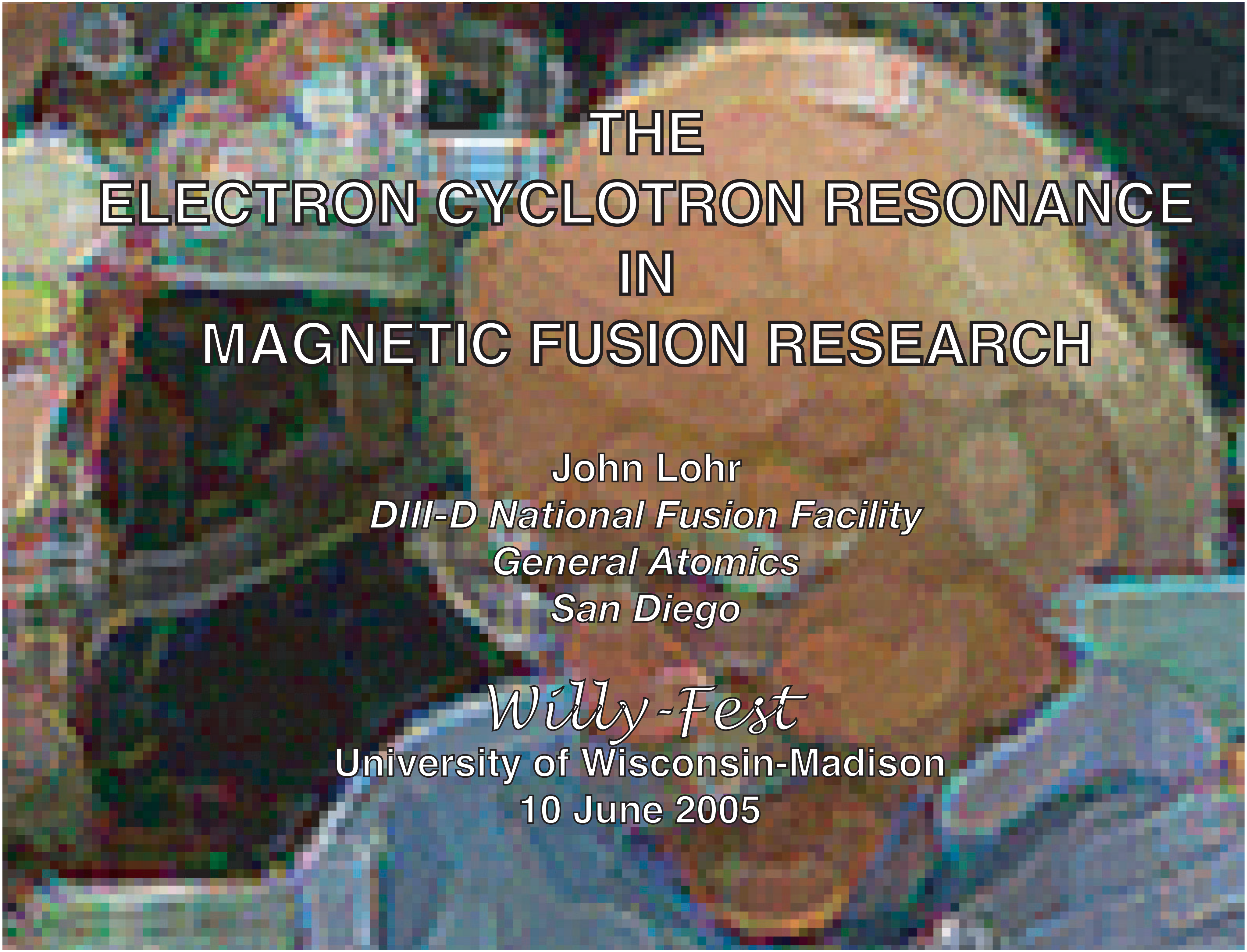

THE
ELECTRON CYCLOTRON RESONANCE
IN
MAGNETIC FUSION RESEARCH

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Willy-Fest
University of Wisconsin-Madison
10 June 2005

Electrons Moving in Magnetic Fields

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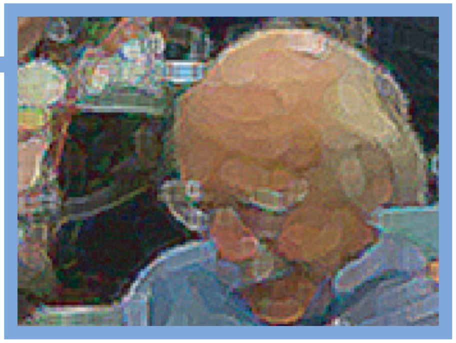
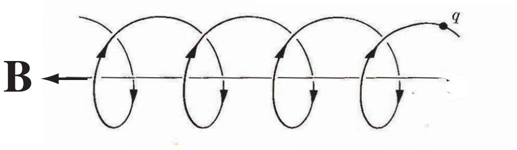
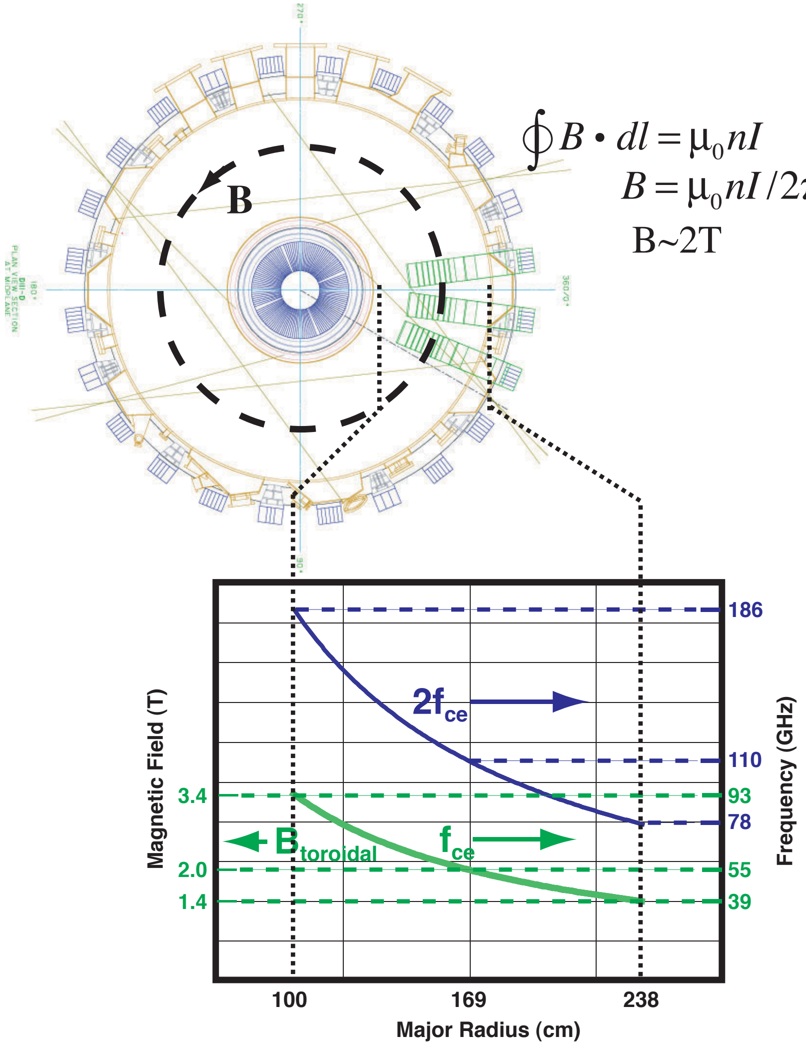




$$\omega = \frac{qB}{\gamma m_e}$$

In a tokamak such as DIII-D, the magnetic field is a function of position in the vacuum vessel, therefore so is the electron cyclotron frequency

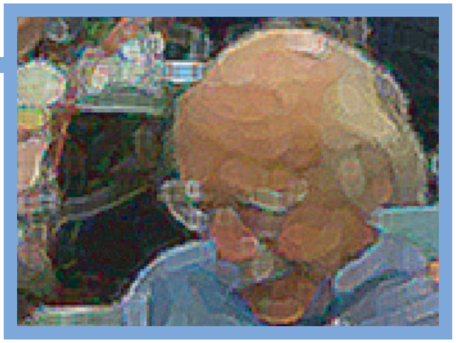


$$\oint B \bullet dl = \mu_0 nI$$

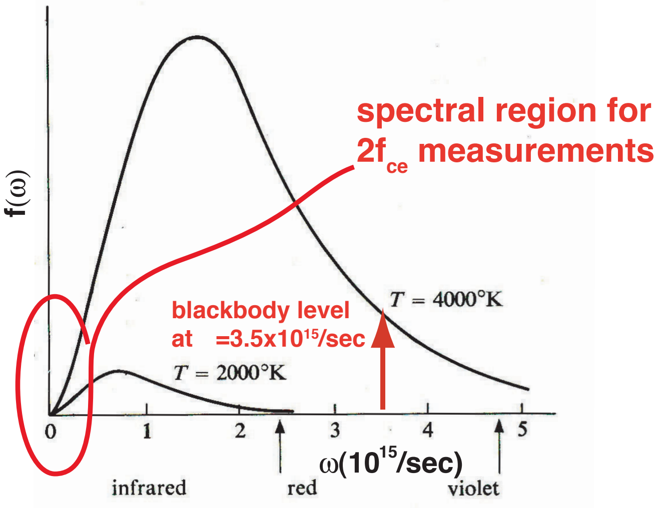
$$B = \mu_0 nI / 2\pi R$$

B~2T

Blackbody Radiation at f_{ce}



In the DIII-D tokamak, T_e~50,000,000 K. The same spectrum applies but the magnetic field restricts emission to discrete cyclotron harmonics.



Because in a magnetized plasma the emission from electrons is only at the local reonant frequency, only emission at this frequency or, in some cases, its harmonics is locally "black" in the sense of having a large optical depth. Emission at this frequency will be at the blackbody limit.

In the non-relativistic limit, the individual plasma electrons radiate power given by

$$P_R = \frac{dW}{dt} = \frac{q^2}{4\pi\varepsilon_0}\,\frac{2}{3}\,\frac{\dot{v}^2}{c^3}$$

but, in a plasma in thermal equilibrium, the blackbody intensity limit applies at any frequency, and the emitted intensity is given by

$$I = \frac{\omega_0 k T_e}{8\pi^3 c^2}\left[1 - e^{-\tau(r)}\right]$$

where $\tau(r)$

is the optical depth, a function of the plasma frequency and electron cyclotron frequency. For most tokamak plasmas, $\tau(r) > 20$ over the entire plasma, therefore, a calibrated receiver with video bandwidth $\Delta\omega$, will detect a signal proportional to the electron temperature

$$P(\omega) = kT_e(r)\frac{\Delta\omega}{2\pi} \sim 10^{-7}\,W,$$

easily detectable with a low noise heterodyne receiver, which gives the electron temperature profile, since the frequency is a function of the radius.

Absorption and Reflection of 2f_{ce} Radiation

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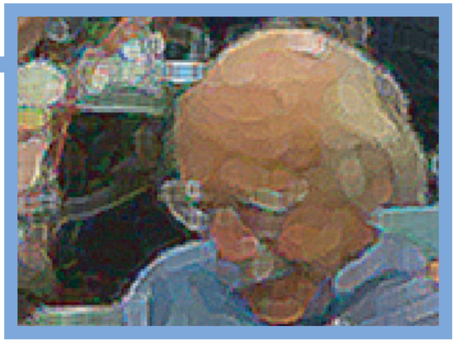
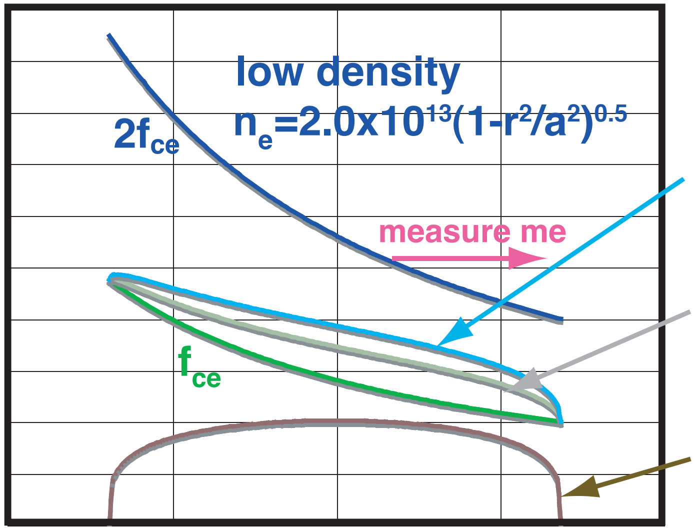




right hand cutoff (X-mode reflected)

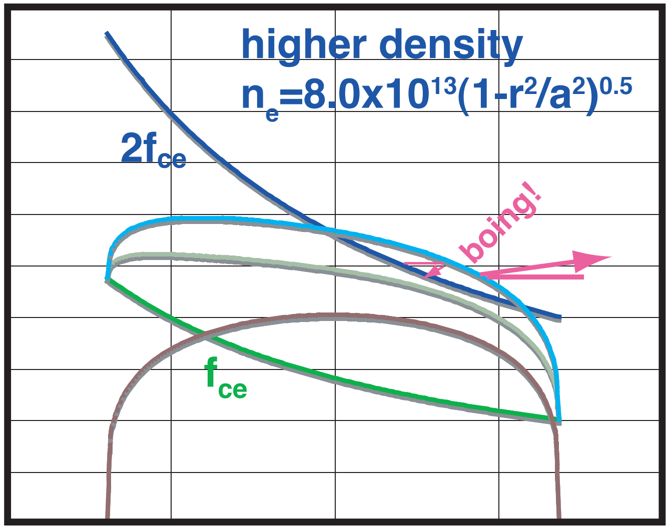
$f_R=0.5[f_{ce}+(f_{ce}^2+4f_{pe}^2)^{0.5}]$

upper hybrid (X-mode absorbed)

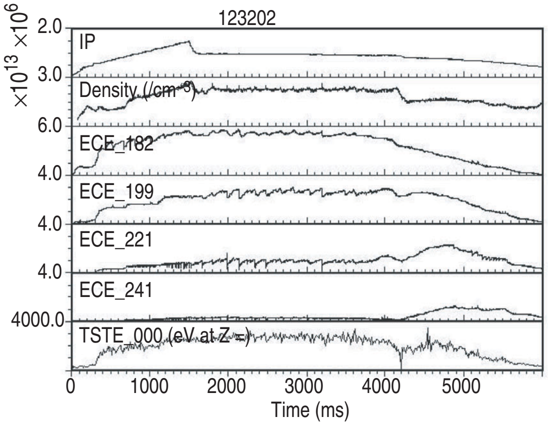
$f_{uh}=(f_{ce}^2+f_{pe}^2)^{0.5}$

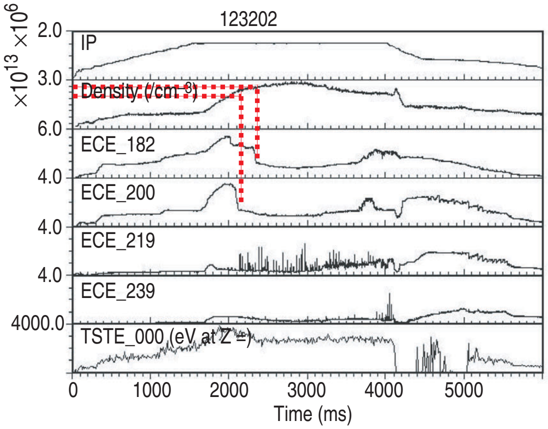
electron plasma frequency

$f_{pe}=9\times10^3\ n_e^{0.5}$

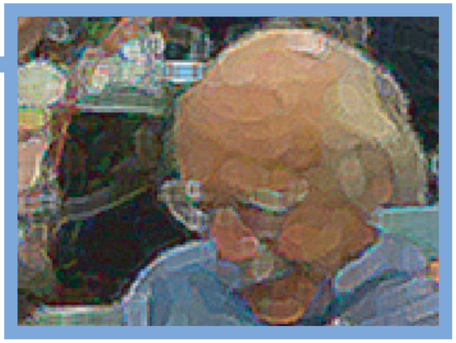


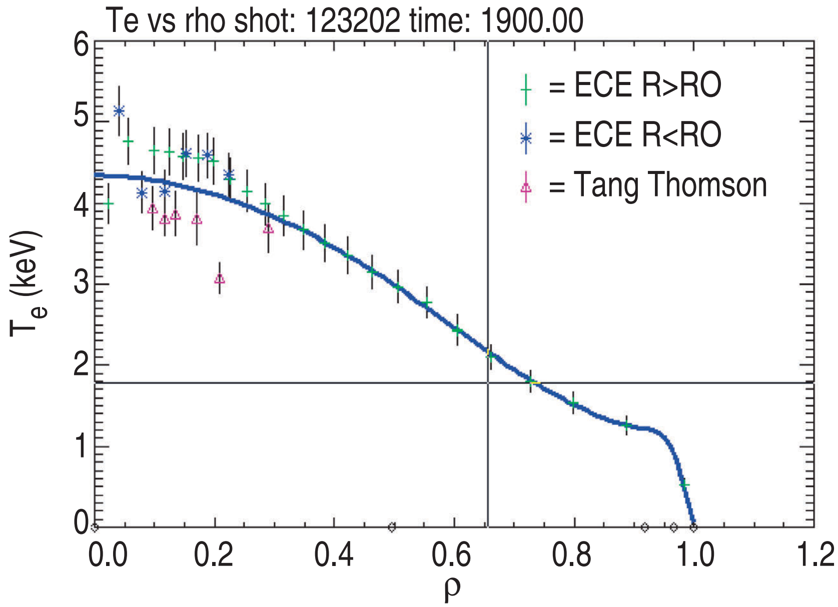
In the low density case, the 2f_{ce} emission gives an accurate measure of the electron temperature profile in the plasma. In the high density case, the emission is reflected and does not reach the observer. Microwaves injected from the outside are also reflected at the right hand cutoff. This is the basis for density and fluctuation measurements by reflectometry.



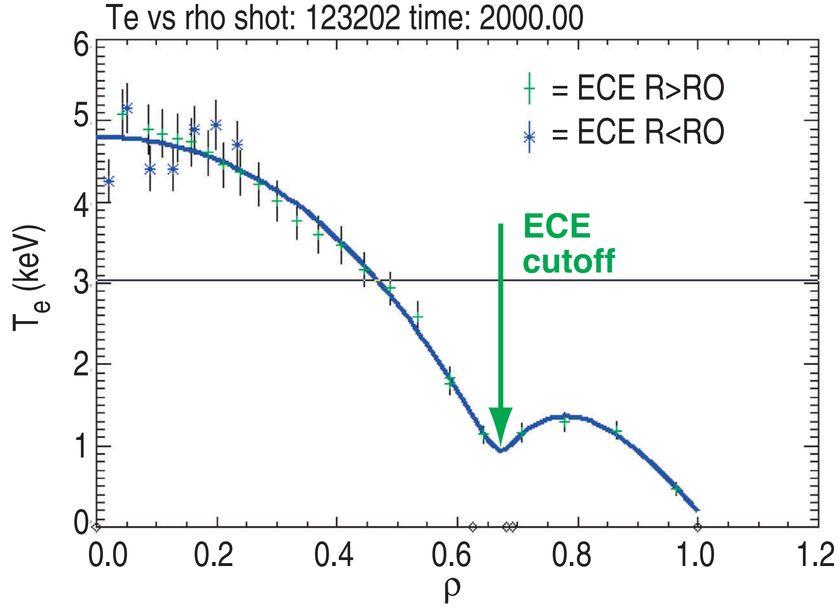


Electron Temperature Profiles from ECE




Te vs rho shot: 123202 time: 1900.00

Profiles of T_e(r) can be obtained with msec time resolution, in this case for a high performance plasma with transport barrier at the periphery.


Te vs rho shot: 123202 time: 2000.00

As the density increases, the electron cyclotron emission begins to be cut off at the reflecting right hand cutoff layer. This provides a crude density measurement.

Heading and Current Drive

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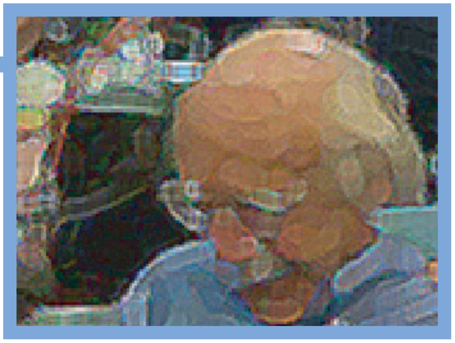

But, actually, measuring microwatt diagnostic signals is for *wimps*. Reciprocity is alive and well, and **REAL MEN** are into injecting into tokamaks megawatts of power at the electron cyclotron resonance and its harmonics. As you might imagine, the power absorption, heating and current drive are highly localized at the location where the electron cyclotron frequency or its harmonics match the microwave frequency of the injected beam. For our system, this is 110 GHz, corresponding to the second harmonic of f_{ce}. Megawatts of rf power at frequencies like this are generated by gyrotrons.

We now increase the power of interest by 13 orders of magnitude and move to heating and current drive.

Gyrotrons for Fusion

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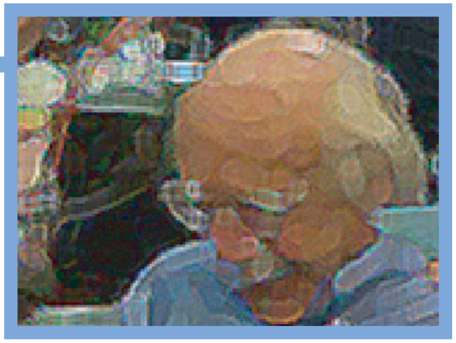
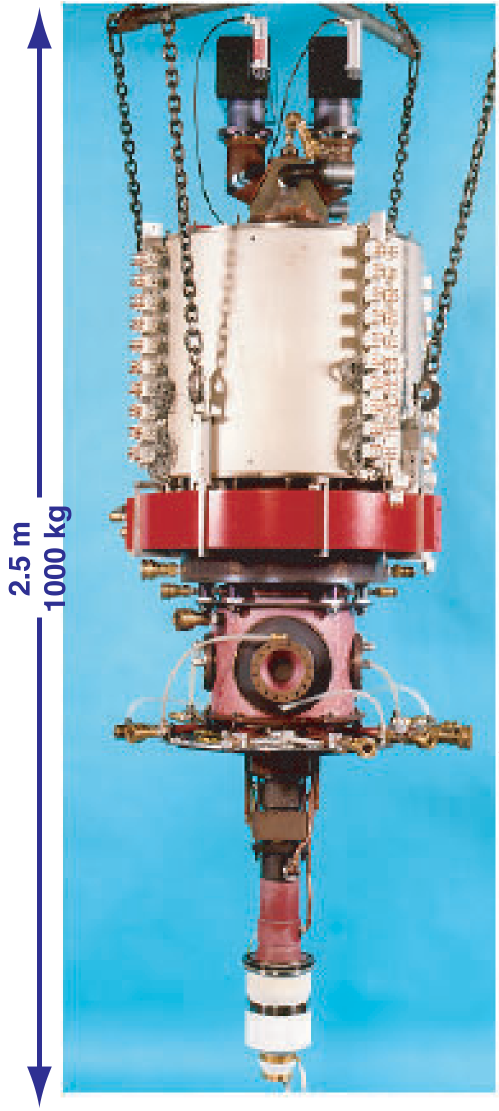
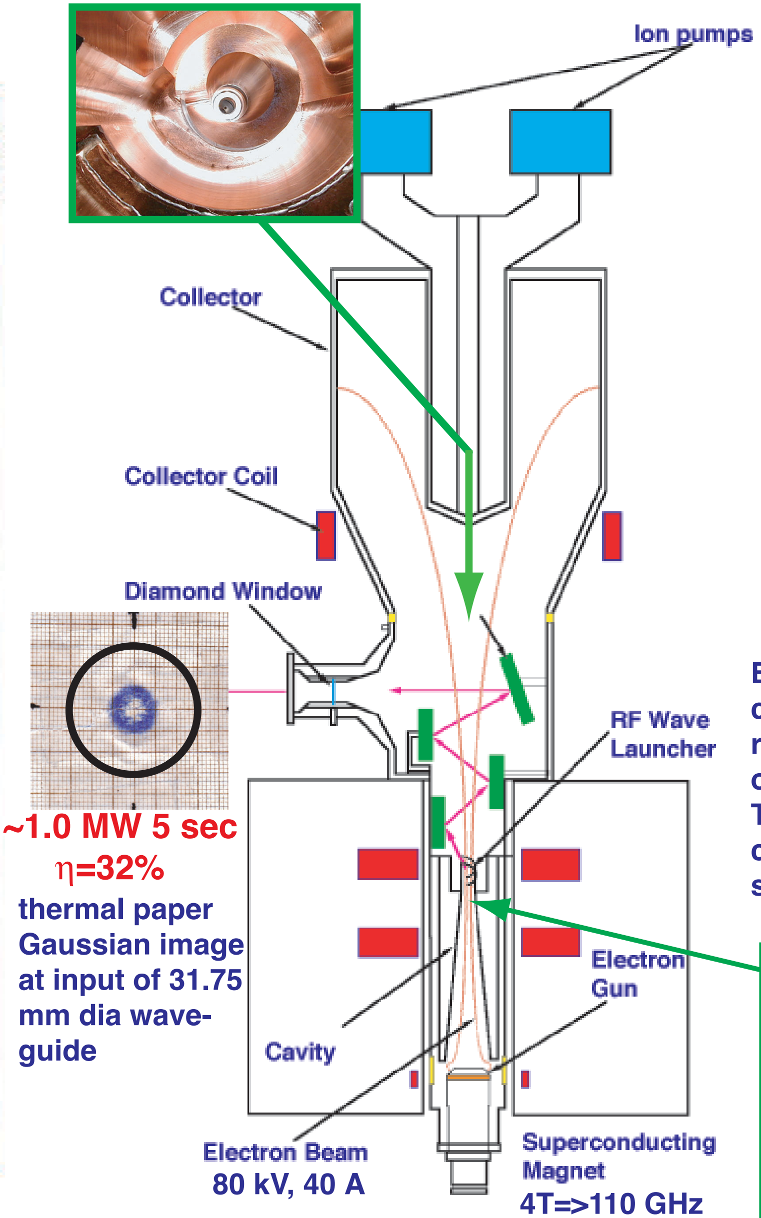




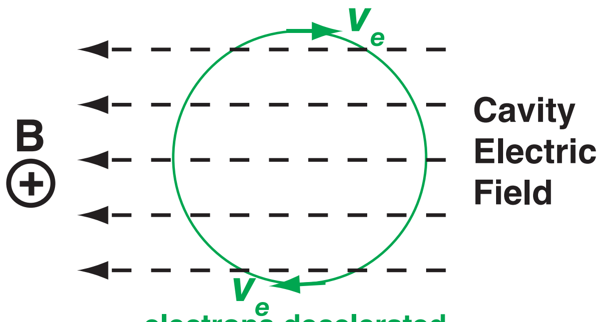


~1.0 MW 5 sec
η=32%
thermal paper Gaussian image at input of 31.75 mm dia wave-guide

Electron Beam 80 kV, 40 A

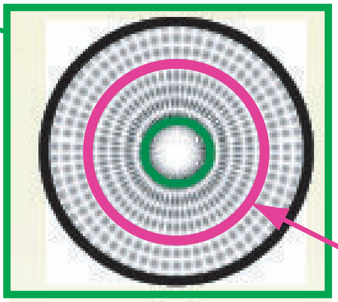
Superconducting Magnet 4T=>110 GHz

electrons accelerated
cyclotron frequency decreases



electrons decelerated
cyclotron frequency increases

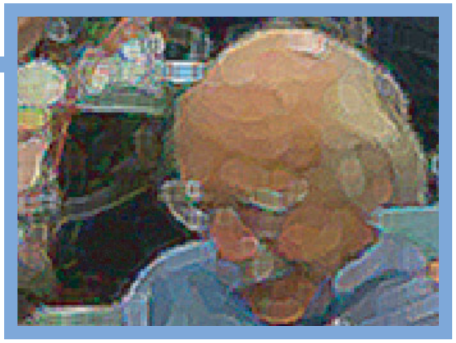
Bunches form in the cavity, which then couple energy into cavity modes. To reduce heating of the cavity walls, high order cavity modes typically are used. The DIII-D gyrotrons operate in the TEM$_{22,6,1}$ cavity mode, which is excited by choosing specific beam and cavity dimensions .



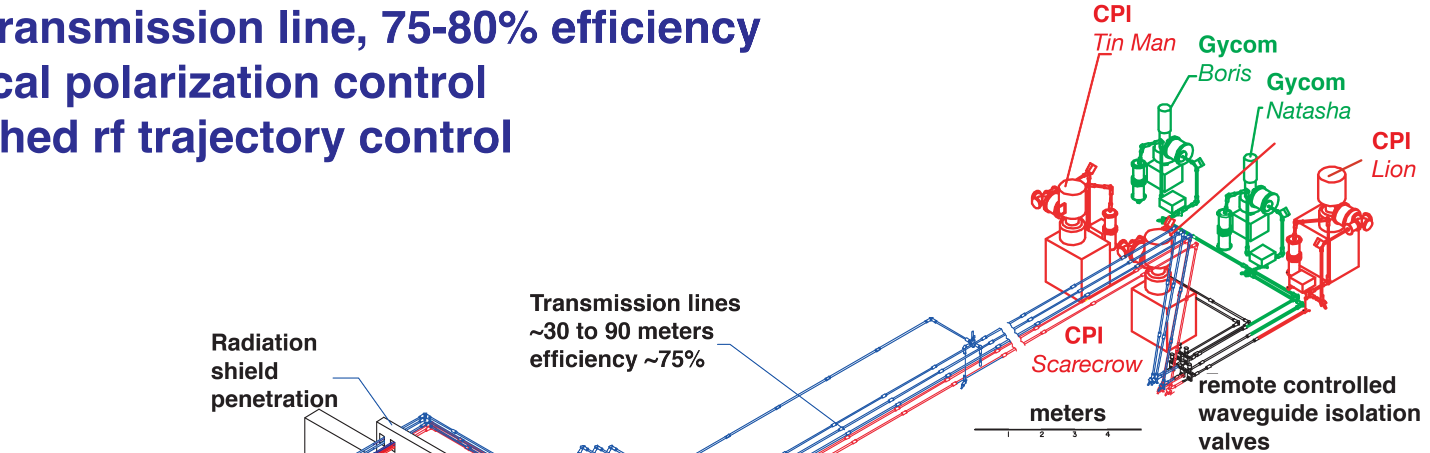
a mode converter produces a free space Gaussian from this high order cavity mode.

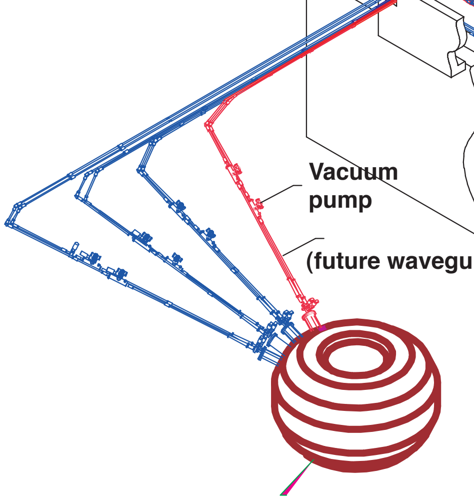
cylindrical electron beam

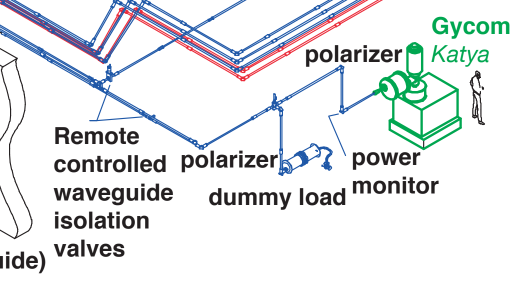
DIII–D Gyrotron Complex



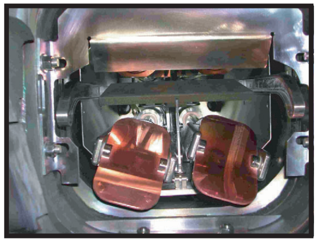
Six gyrotrons
5.0 MW generated power at 110 GHz
3.5 MW injected into the tokamak
90 m transmission line, 75-80% efficiency
Elliptical polarization control
Launched rf trajectory control



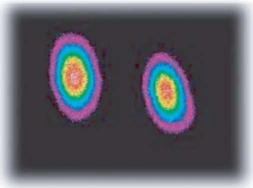




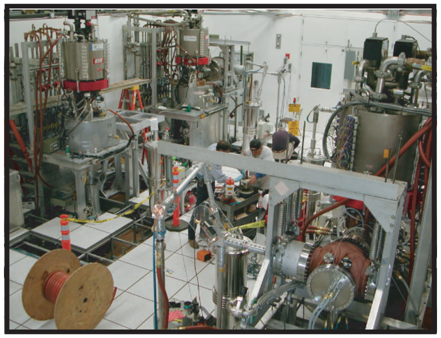
DIII-D Tokamak



steerable launcher in tokamak

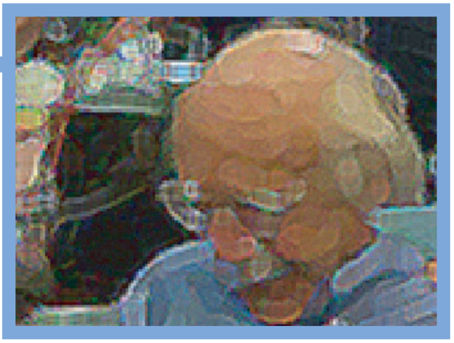


IR image of rf beams at the tokamak center

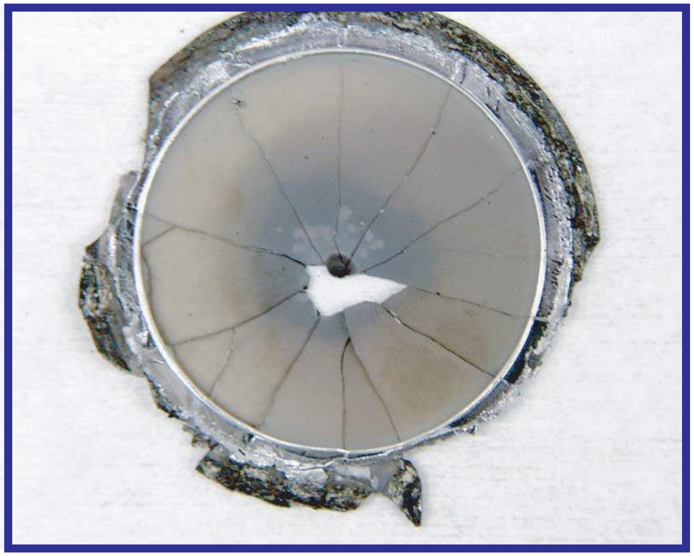


gyrotron vault

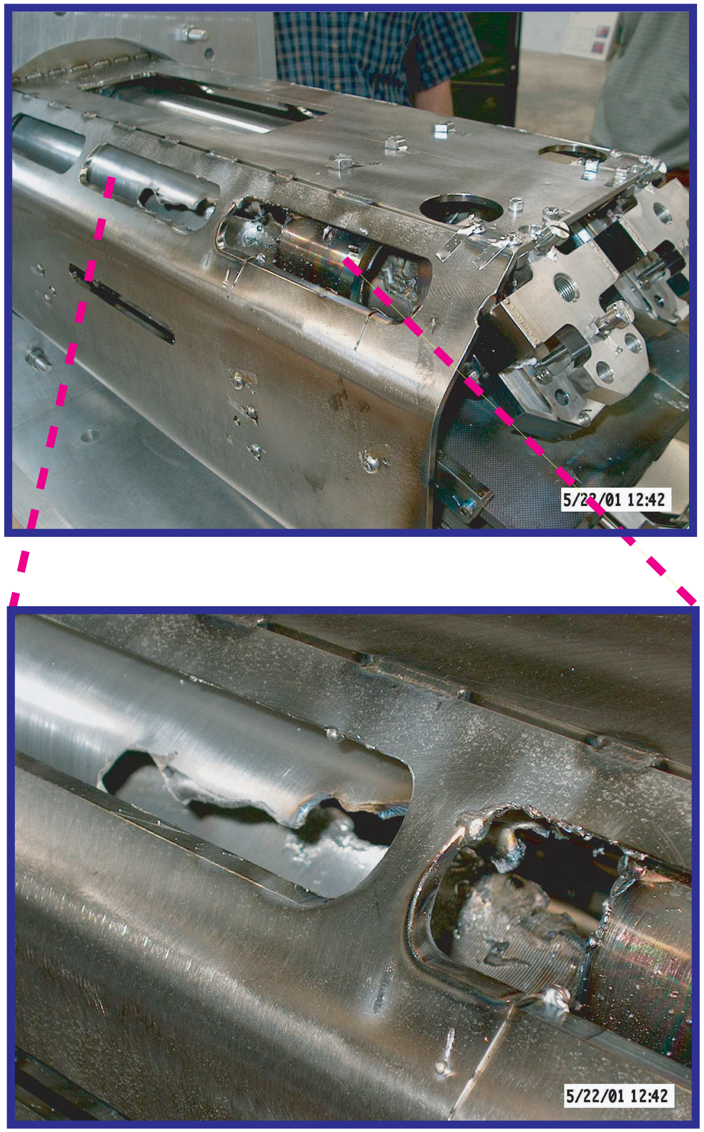
Big Power is Fun



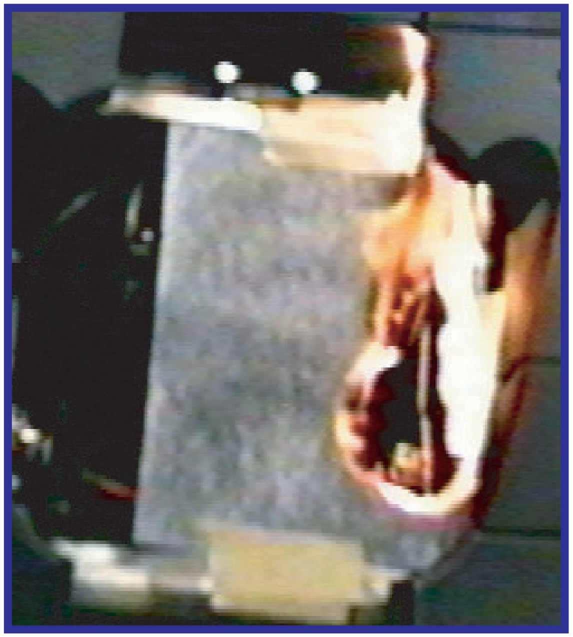
...and not for the faint of heart



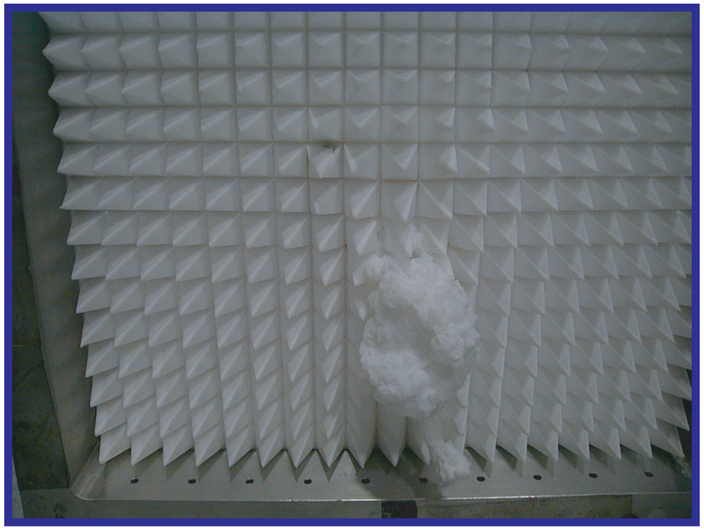
CVD diamond output window ($100k)



Articulating launcher melted in the tokamak



Fire in the tokamak (fortunately late at night)



Fancy teflon free space dummy load

What can you do with it?

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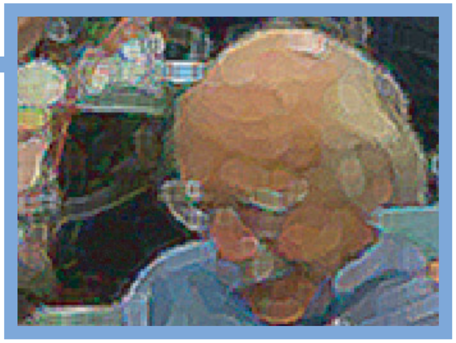
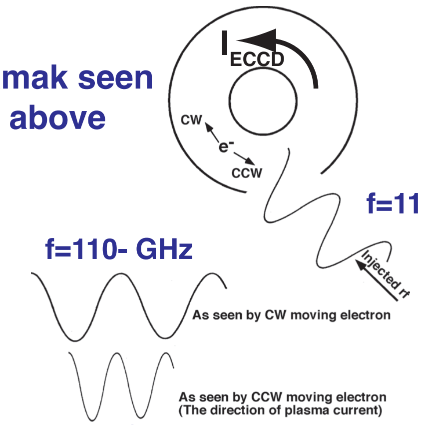


...heat and drive current where and when you want

Electrons moving CW see a Doppler downshifted frequency, therefore for this oblique injection, electrons at lower magnetic field, outside the nominal second harmonic resonance, will absorb the rf and be heated. This reduces their collision cross section with the background, resulting in a positive current in the opposite direction. Electrons going the other way inside the resonance would be preferentially heated, canceling the effect, except the rf power was already absorbed further out. This was predicted by Fisch and Boozer in 1980.

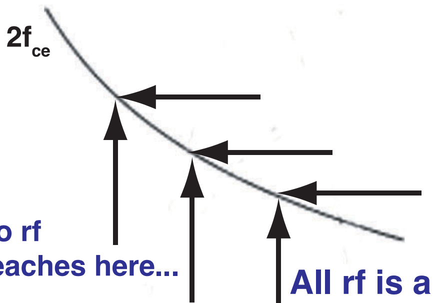


Tokamak seen from above

f=110 GHz

f=110- GHz

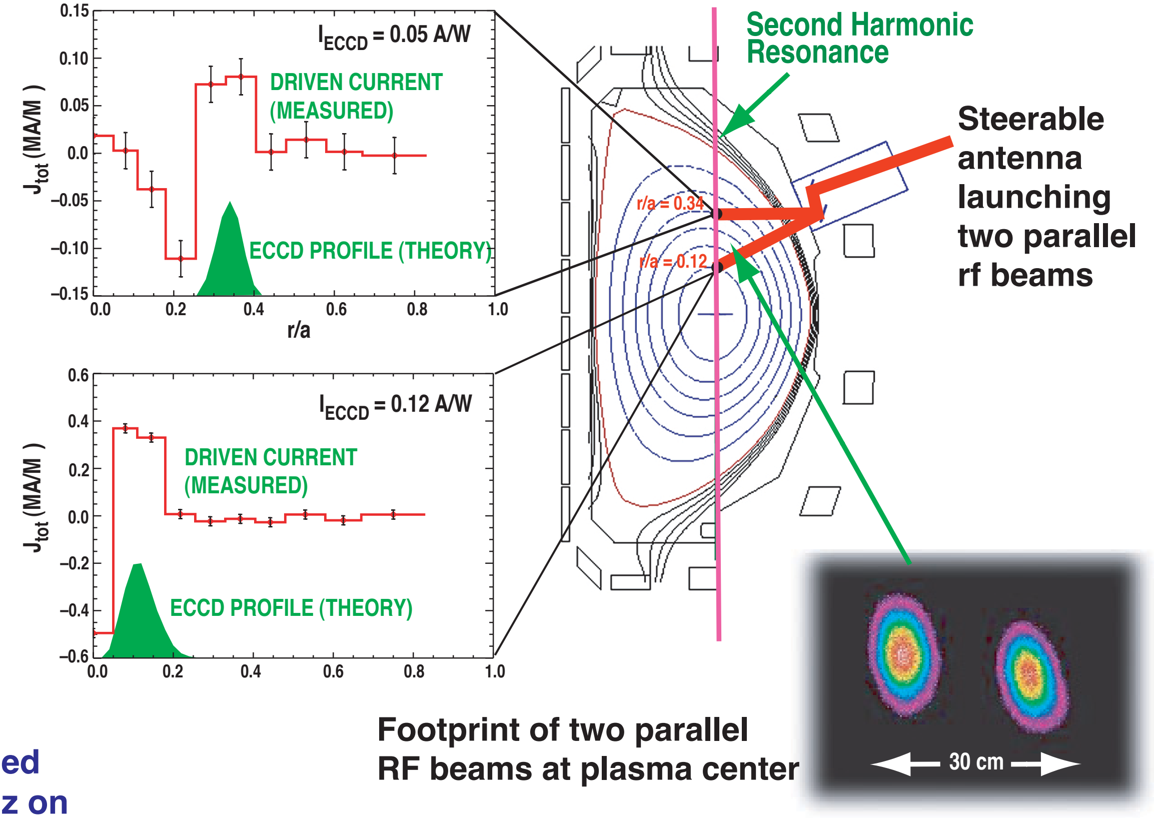
f=110+ GHz



no rf reaches here...

...or here

All rf is absorbed at $2f_{ce}$=110- GHz on electrons moving CW, they get hotter, their friction on the ions decreases and a CCW positive current results



Second Harmonic Resonance

Steerable antenna launching two parallel rf beams

Footprint of two parallel RF beams at plasma center

NTM Suppression with ECCD

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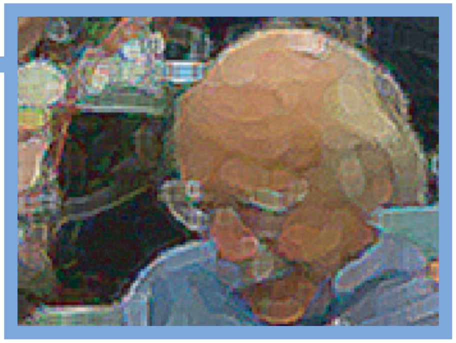
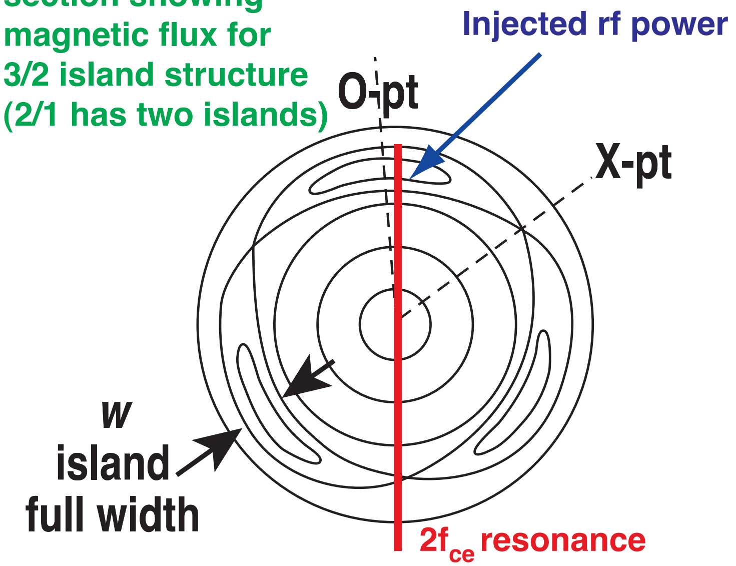
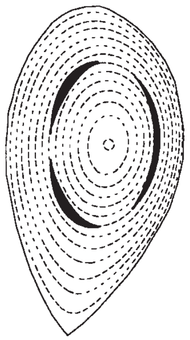
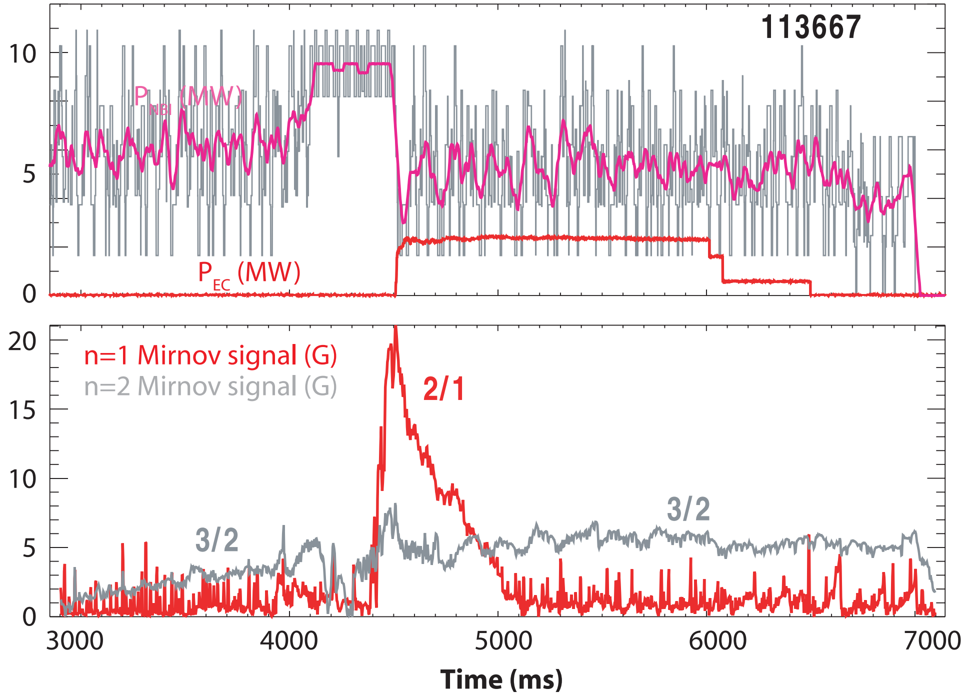


Schematic poloidal cross section showing magnetic flux for 3/2 island structure (2/1 has two islands)





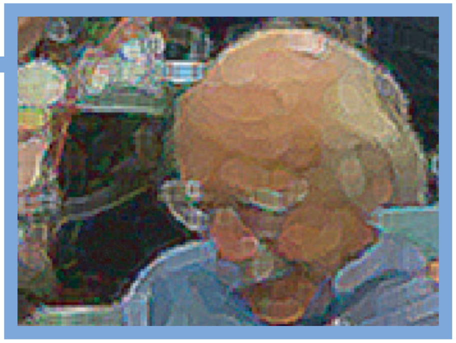
A real flux plot showing the m/n=3/2 islands in a poloidal view



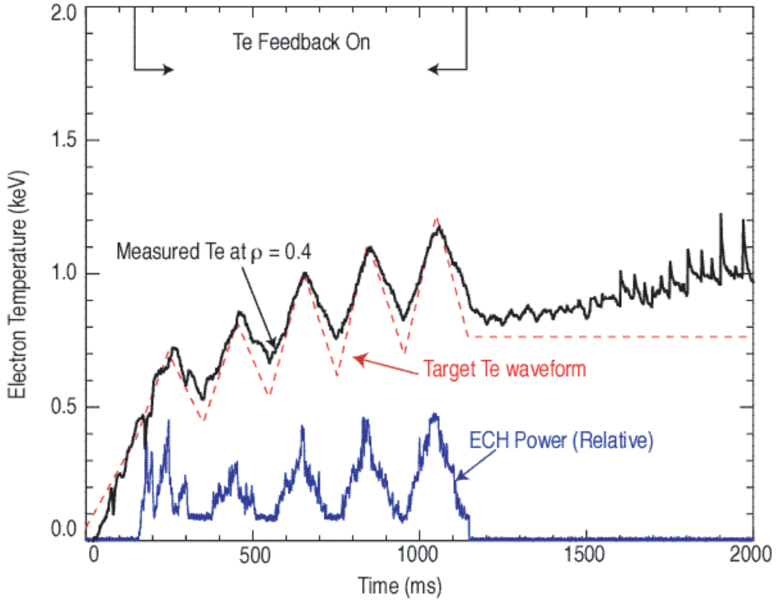
The neoclassical tearing mode shows up as rotating island structures at rational q surfaces where magnetic field lines close on themselves. The islands appear because of a local reduction of plasma current which occurs at locations where there is a plateau in the pressure profile. The NTM, particularly the m/n=2/1 mode, is a precursor to disruption of the plasma, which in a very large tokamak can cause damage. Restoring the missing current with electron cyclotron current drive at the cyclotron resonance can completely kill this instability. This is a big deal.

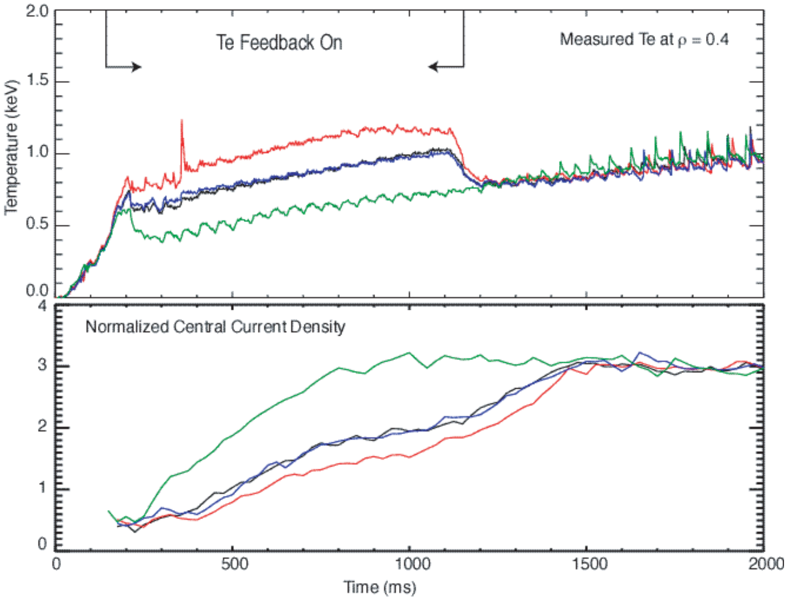
In this case, 2.3 MW of rf power driving current at the island location, kills the tearing mode.

Modulated ECH Feedback Control



The DIII-D plasma control system compared Te measured by ECE at a specific location with a target Te evolution and modulated the ECH power to meet request.





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.

T_e(t) control was then used to affect the rate of current penetration early in the discharge. Here, lower target temperature gave more rapid current penetration.

Conclusion

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We ought to have fusion power before Willy runs out of gas
...thanks for the ride

International Symposium on
Polarization of Nucleons
Basel July 1960