Absorption of X-Wave at the Second Harmonic in HSX

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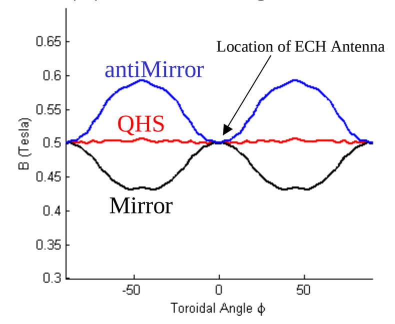
Abstract

Second harmonic extraordinary mode ECH is used in the HSX stellarator at 0.5 T to break down and heat the plasma. To measure the absorbed power a set of absolutely calibrated microwave diodes have been installed inside the machine. In the QHS and Mirror configuration, the absorption efficiency is high (about 0.9) and drops (0.6) in the anti-Mirror mode. A comparison with ray tracing predictions is made.

HSX Main Parameters

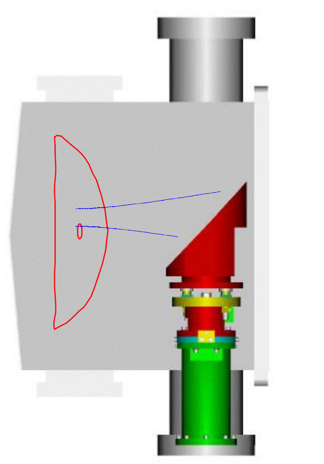
Major Radius	**1.2 m**
Mean plasma radius	**0.15 m**
Volume	**~.44 m^3**
Field Periods	**4**
Rotational transform	**1.05 – 1.12**
Coils/period	**12**
B_0 (max.)	**1.25 T**
Magnetic Field Flattop Length	**0.2 s**
Auxiliary Coils	**48**

|B| vs. Toroidal Angle on Axis.



- Mod |B| ripples are small in QHS configuration
- In Mirror mode the heating takes place on mod |B| hill while in anti-Mirror mode in the well.

EC Heating in HSX



- Microwave power (up to 100 kW at 28 GHz) is used for neutral gas breakdown followed by heating of plasma at the second harmonic of electron cyclotron frequency.
- Linear polarized beam with **E** perpendicular to **B** is launched from the low magnetic field side and is focused on the plasma center in a spot of 4 cm in diameter.

Ray-Tracing Equations

$$\frac{d\vec r}{dt} = -\frac{\partial G/\partial \vec k}{\partial G/\partial \omega}$$

Cold plasma dispersion relation

$$G(\vec r,\vec k,\omega) = \frac{c^2\vec k^2}{\omega^2} - N^2(\vec r,\vec k,\omega) = 0$$

$$\frac{d\vec k}{dt} = \frac{\partial G/\partial \vec r}{\partial G/\partial \omega}$$

Altar-Appleton-Hartree formula

$$N^2(\vec r,\vec k,\omega) = 1 - \frac{\omega_{pe}^2(\omega^2-\omega_{pe}^2)/\omega^2}{\omega^2-\omega_{pe}^2-0.5\cdot\Omega_e^2\sin^2\theta \mp \Delta}$$

$$\frac{dP}{dt} = -2\cdot \mathrm{Im}|k_j|\cdot|V_{gr}|\cdot\cos(\alpha)\cdot P \qquad \Delta = \sqrt{0.25\cdot\Omega_e^4\sin^4\theta + \Omega_e^2\omega^{-2}(\omega^2-\omega_{pe}^2)^2\cos^2\theta}$$

Im$|k_j|$ - absorption coefficient; V_{gr} – group velocity;
α - angle between $\boldsymbol{V}_{gr}$ and $\boldsymbol{k}_j$.

Electron Cyclotron Damping

- Resonance condition: $\omega = n\cdot\Omega_e + k_{\|}\cdot v_{\|}$

  where $\Omega_e = \frac{eB}{m_o c\sqrt{1+\left(v_{th}/c\right)^2}}$

- Extraordinary wave at the second harmonic of Ω_e

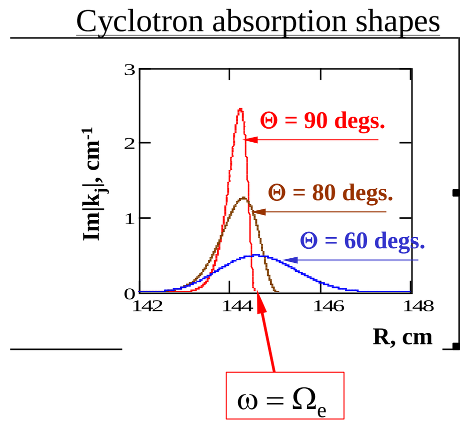
$$\frac{\mathrm{Im}|k_e|}{k_e} = \frac{2\pi}{15}q\cdot\left(\frac{3-0.5q}{3-q}\right)^2\cdot z^{\frac{5}{2}}\cdot e^{-z} \quad \text{for} \quad \theta=\frac{\pi}{2}$$

$$\frac{\mathrm{Im}|k_e|}{k_e} = \frac{\pi}{4}q\cdot\left(\frac{3-0.5q}{3-q}\right)^2\cdot\left(\sqrt{1+2z/a}\right)^{\frac{3}{2}}\cdot I_{\frac{3}{2}}\left(a\sqrt{1+2z/a}\right)\cdot e^{-(z+a)} \quad \text{for} \quad \left|\frac{\pi}{2}-\theta\right| << 1$$

where $a = \frac{mc^2}{T_e}\cdot\frac{3-2q+0.5q}{3-q}$ $\quad q = \frac{\omega_{pe}^2}{\Omega_e^2}$ $\quad z = \frac{2\Omega_e-\omega}{\Omega_e v_{th}^2/c^2}$

Perpendicular and Oblique Propagation

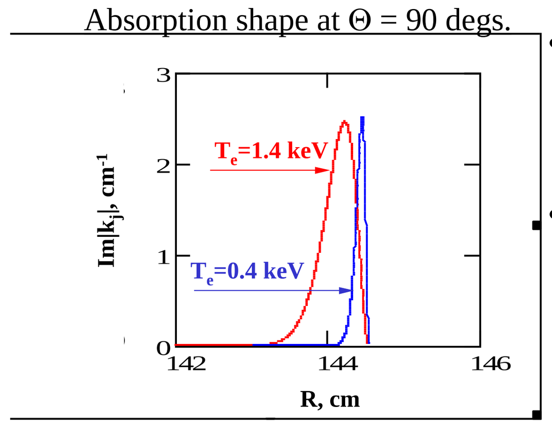
Cyclotron absorption shapes



- At Θ = 90 degs. absorption occurs at $\Omega_e > \omega$
- Absorption efficiency drops with $\mathbf{k}_{parallel}$
- At large $\mathbf{k}_{parallel}$ the absorption is symmetric with respect to resonance point

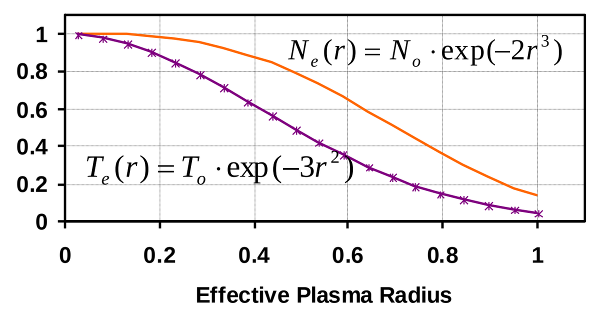
Temperature effect

Absorption shape at Θ = 90 degs.



- The cyclotron absorption shape is broadened with temperature
- At Θ = 90 degs. the maximum is moved inward due to relativistic mass increase

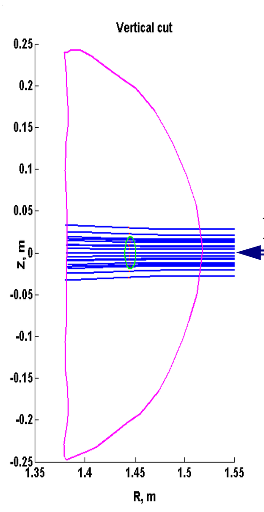
Plasma Density and Electron Temperature Profiles



These profiles are used in the ray tracing calculations

- Plasma density profile is interpolated interferometer data

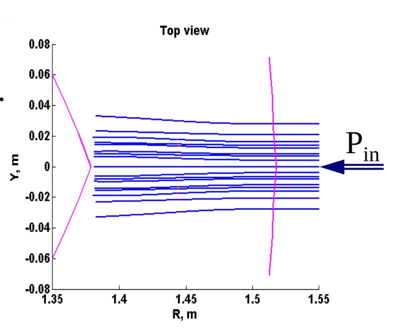
Ray Trajectories



17 rays

r_{in} = 3 cm

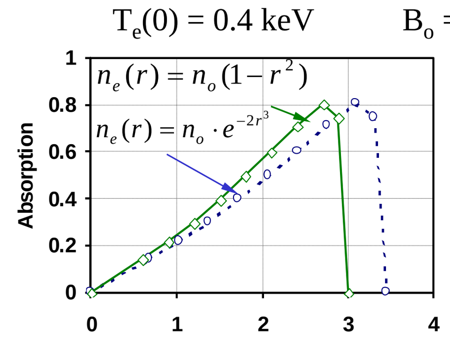
Θ = 0 degs.



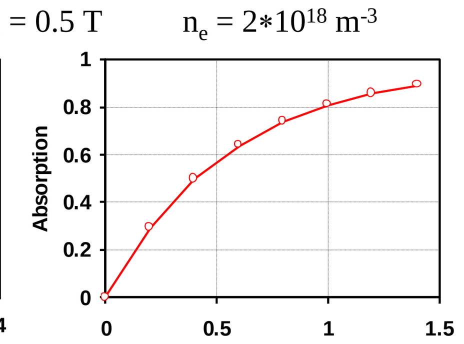
$n_e = 2\cdot10^{18}$ m^{-3} , B_o = 0.5 T

Single-pass Absorption

$T_e(0)$ = 0.4 keV $\quad B_o$ = 0.5 T $\quad n_e = 2\cdot10^{18}$ m^{-3}

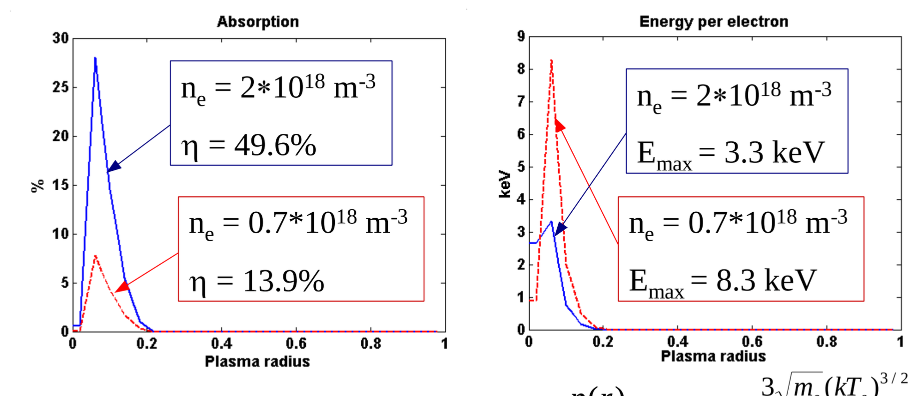


Small refraction: narrow beam propagates almost along grad|n_e| and grad|B|.



At 1 keV the single-pass absorption is 0.8

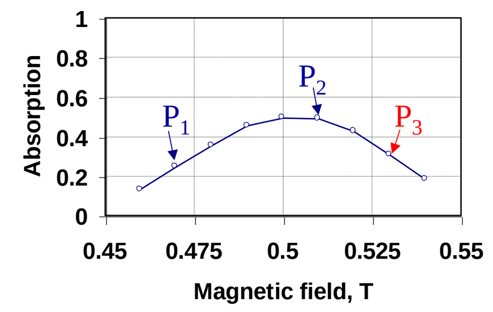
Absorbed Power Profile



P_{in} = 100 kW
$T_e(0)$ = 0.4 keV, B_o = 0.5 T

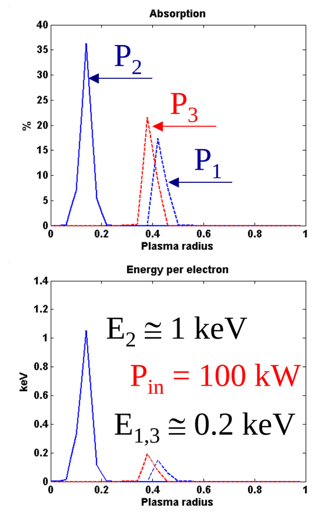
$$q(r) = \frac{p(r)}{V\cdot n_e}\cdot\tau_e \qquad \tau_e = \frac{3\sqrt{m_e}(kT_e)^{3/2}}{4\sqrt{2\pi}n_e\Lambda e^4}$$

Magnetic Field Scan

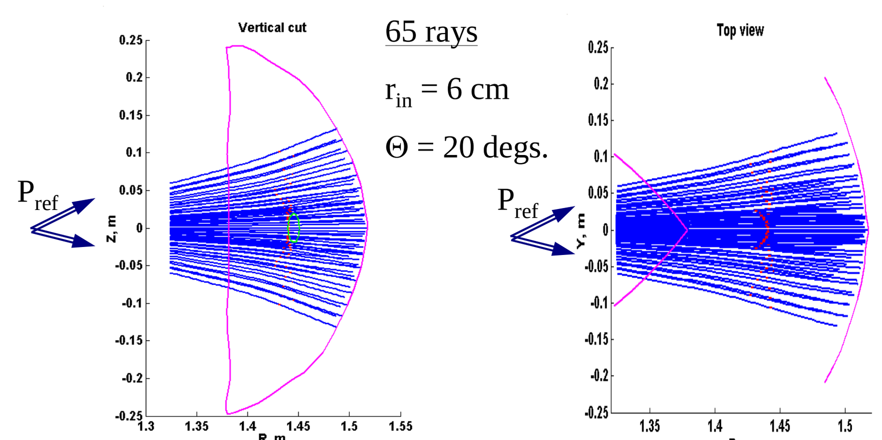


$n_e = 2\cdot10^{18}$ m^{-3}, $T_e(0)$ = 0.4 keV

- Shift out of the central resonance reduces the absorption

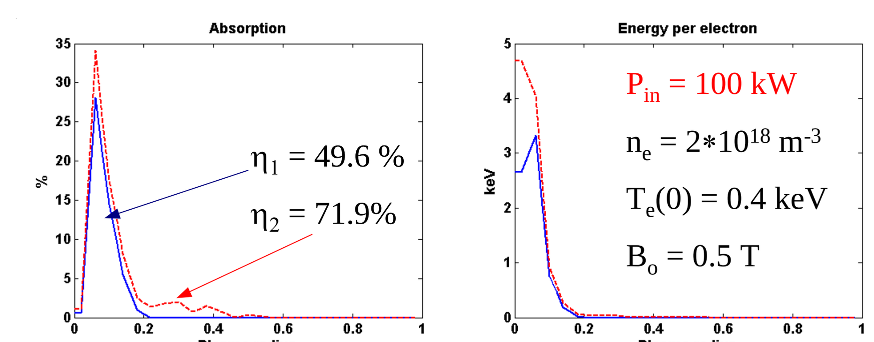


Reflection From The Wall



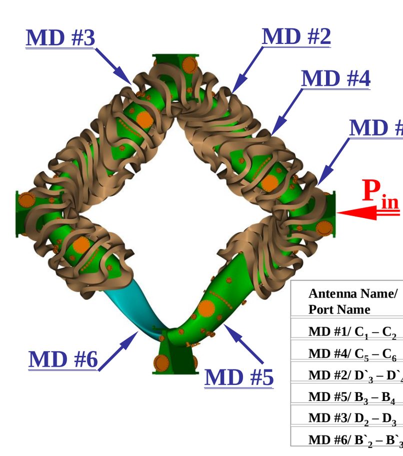
$n_e = 2\cdot10^{18}$ m^{-3} , B_o = 0.5 T

Second Pass vs. the First One



- Second pass increases the absorption
- Absorbed power profile is not broaden much
- Energy per particle in the center rises

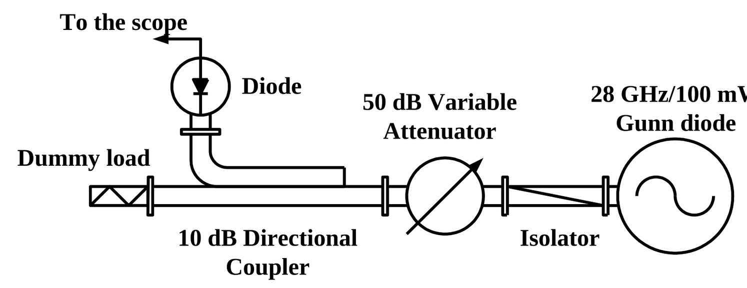
Location 0f Antennas



- Each antenna consists of an open K-band waveguide, attenuator and microwave detector

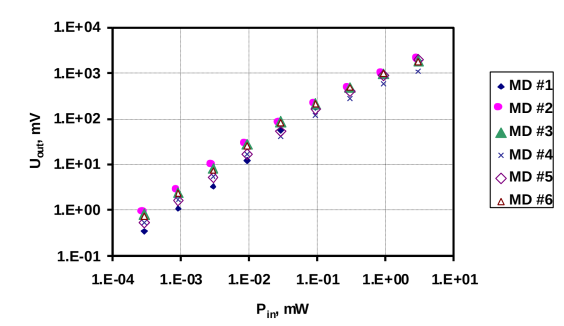
Antenna Name/ Port Name	Toroidal Angle, degs.	Distance from ECH port, m	Area Of HSX Helical Cut, m^2
MD #1/ C_1 – C_2	6.3	0.181	0.12
MD #4/ C_5 – C_6	36.0	0.942	0.1188
MD #2/ $D`_3$ – $D`_4$	69.3	1.675	0.1297
MD #5/ B_3 – B_4	-69.3	1.675	0.1297
MD #3/ D_2 – D_3	103.5	2.642	0.1264
MD #6/ $B`_2$ – $B`_3$	-103.5	2.642	0.1264

Calibration of Diodes



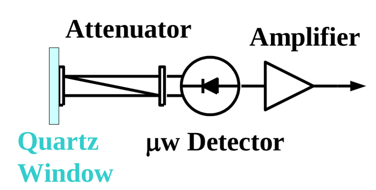
- The microwave source and the line are calibrated with thermistor mount, first, and then the diodes.

Calibration Curves



- Six diodes are almost identical
- The square law is up to about 30 μW of input power

Power at each toroidal location

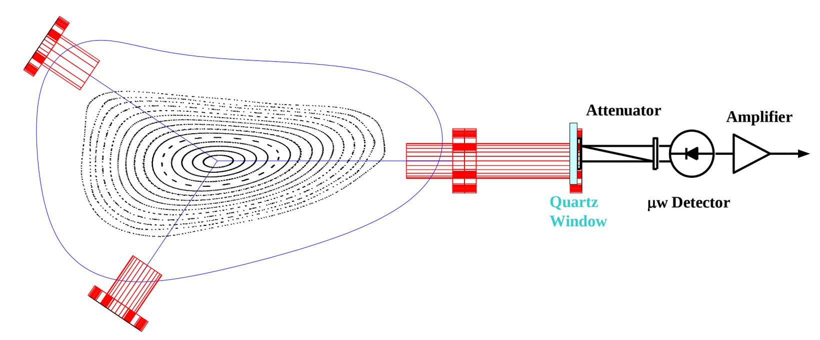


- Power at each toroidal location:

$$P_{non} = \frac{U_i}{G_i}\cdot S_i\cdot\frac{S_v}{Wg\cdot Att\cdot trs_w}$$

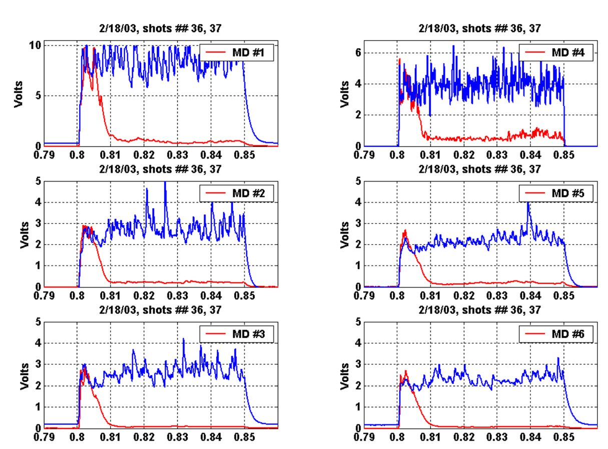
U_i – acquired signal; G_i – gain of the amplifier; S_i – diode sensitivity; Att – attenuation coefficient of the attenuator; trs_w – transparency coefficient of the quartz window; Wg – area of waveguide cross-section; S_v – area of the HSX helical cut

C5-C6 HSX Port



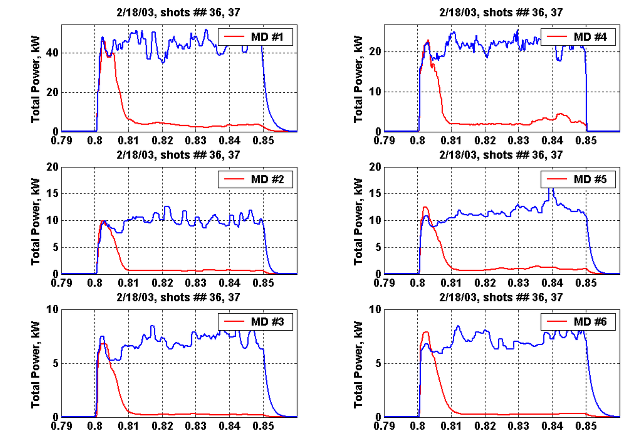
- Antennas are mounted on 5" extension nipples

Raw signals



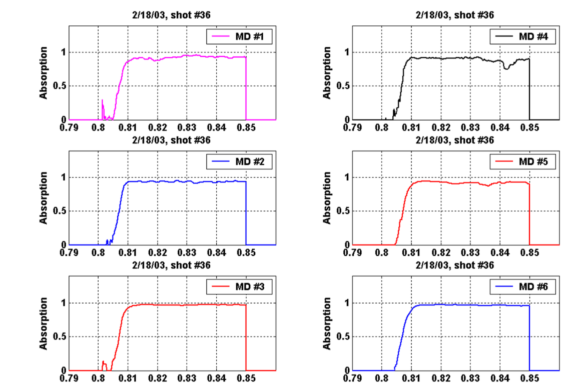
In shot #36:
$n_e = 1.5\cdot10^{18}$ m^{-3}
W_E = 22 J
In shot #37:
$n_e = 3.1\cdot10^{18}$ m^{-3}
W_E = 1.6 J

ECH Power along the HSX



In shot #36:
$n_e = 1.5\cdot10^{18}$ m^{-3}
W_E = 22 J
In shot #37:
$n_e = 3.1\cdot10^{18}$ m^{-3}
W_E = 1.6 J

Absorption coefficients

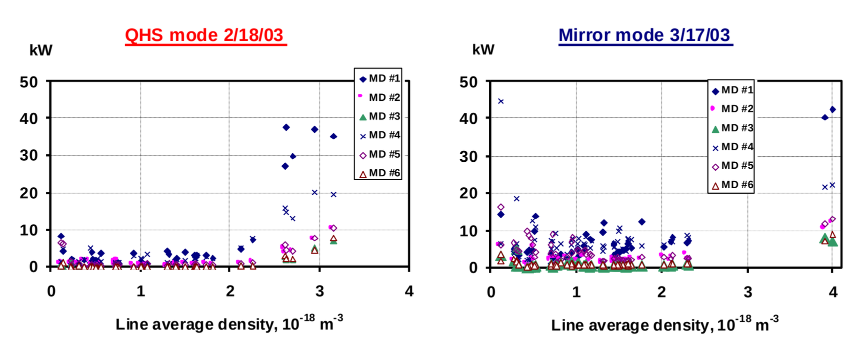


In shot #36:
$n_e = 1.5\cdot10^{18}$ m^{-3}
W_E = 22 J

- Absorption coefficient: $\eta = 1 - P_{non}/P_o$, where P_{non} – non-absorbed power, P_o - power in "cold" plasma discharge (at high plasma density)

Plasma Density Scan

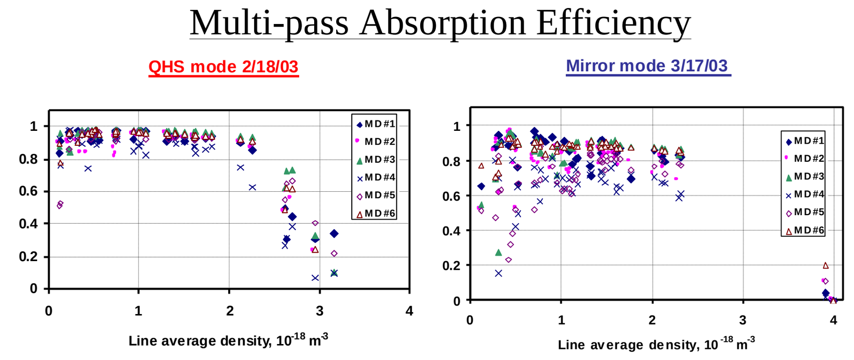
Non-absorbed ECH Power



- Launched Power is about 40 kW in both cases

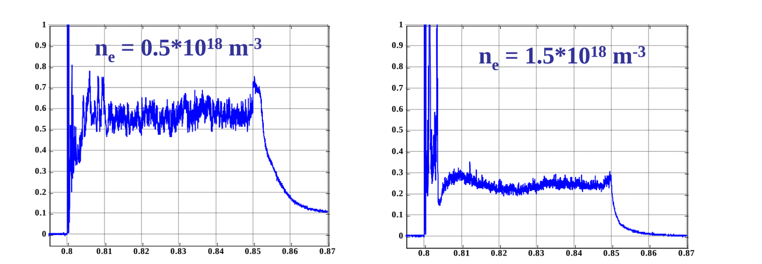
Plasma Density Scan (cont.)

Multi-pass Absorption Efficiency



- In QHS and Mirror configurations the absorption is high (0.8-0.9). At low plasma densities the error of this method can be big enough due to wave interference.

ECE measurements



- In QHS mode the ECE signal is about a factor of 3 higher at low plasma density than at high plasma density.
- It might be due to high plasma temperature and some population of superthermal electrons