Abstract Submitted
for the DPP99 Meeting of
The American Physical Society

Sorting Category: 5.1.1.2 (Theoretical)

Sensitivity of Calculated Electron Cyclotron Current Drive to Variations of Parameters Around DIII-D Tokamak Conditions[1] R.W. HARVEY, CompX, Y.R. LIN-LIU, C.C. PETTY, T.C. LUCE, R. PRATER, General Atomics — Off-axis Electron Cyclotron (EC) Current Drive (CD) efficiency in the DIII–D tokamak has been observed[2] to exceed calculated results obtained from axisymmetric, Fokker-Planck theory.[3] This study reports on calculated current resulting from variations of plasma parameters around the measured profiles, to assess the differences required to bring theory into conformity with experiment. Alternatively, and presently without a theoretical basis, the strength of the quasilinear diffusion coefficient D_{ql} has been varied from theory. A factor of ≈ 2 increase in D_{ql} increases central CD by 30% but increases mid-radius CD by a factor of 5, giving agreement between experiment and calculation within the error bars.

[1]Work supported in part by U.S. DOE Contract DE-AC03-98ER54463 and Grant DE-FG03-99ER54541.
[2]T.C. Luce *et al.*, IAEA Fusion Energy Mtg., Japan, 1998.
[3]R.W. Harvey and M.G. McCoy, IAEA TCM on Advances in Simulation and Modeling of Thermonuclear Plasmas, Montréal, 1992, p. 527 (IAEA, Vienna, 1993).

- [ ] Prefer Oral Session
- [X] Prefer Poster Session

R.W. Harvey
bobh@compxco.com
CompX

Special instructions: DIII-D Poster Session 2, immediately following TA Casper

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Sensitivity of Calculated Electron Cyclotron Current Drive to Variations of Parameters Around DIII-D Tokamak Conditions†

Poster at 1999 APS/DPP Annual Meeting, Seattle

Outline

- **Off-Axis ECCD exceeding theoretical calculations has been observed in DIII-D (Expt. = 30 kA, Theory = 7.5 kA, at $\rho = 0.5a$).**
- **A well-benchmarked Fokker-Planck code (CQL3D) gives the theoretical EC current drive.**
- **Examination of ray trajectory data shows that damping is occuring on electrons with velocity in the neighborhood of v_{Te}.**
- **Variation of the T_e, n_e, and Z_{eff} around the nominal experimental parameters confirms that:**
  $\Longrightarrow$(1) (Too) Large parameter variations would be required to explain the observations.
  (2) "Good" theoretical off-axis ECCD efficiency is predicted at higher T_e (in case present fortuitous results don't scale).
- **Variation of strength of an *ad hoc* QL diffusion coefficient multiplier**
  $\Longrightarrow$ Factor of 2 increase in D_{QL} strength above theory
  $\Longrightarrow$ Rough agreement between expt. and calc.
- **An explanation of increased "diffusion" beyond QL theory is being explored (large amplitude, finite spot size effects).**

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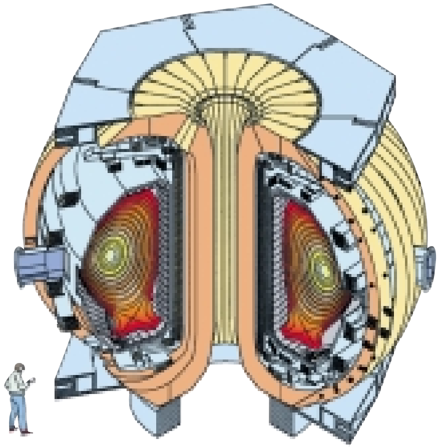
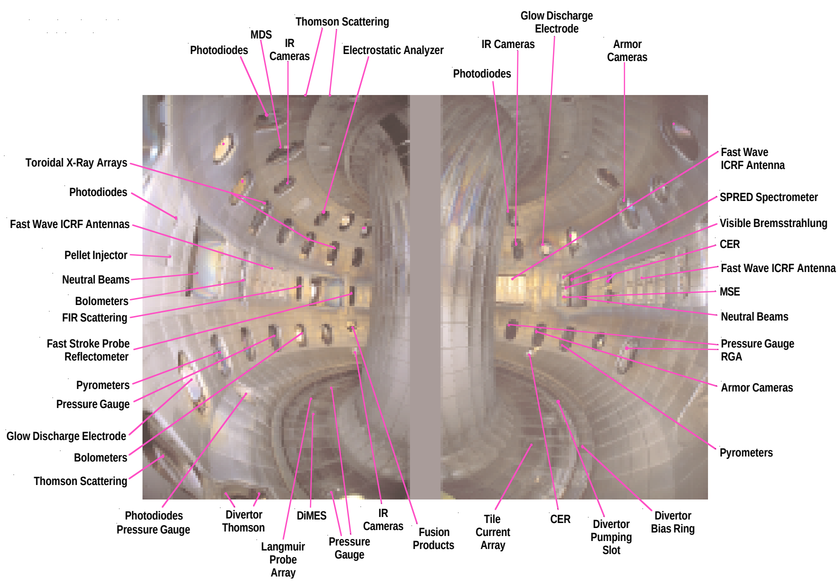
†R.W. Harvey, CompX, Del Mar, CA,
Y.-R. Lin-Liu(GA), C.C. Petty, T.C. Luce(GA), R. Prater(GA)

DIII–D PROGRAM HAS ESTABLISHED GA AS A NATIONAL FUSION RESEARCH CENTER

Flexibility and Control Capability



Well Diagnosed Plasma
>60 diagnostic systems



Broadbased Participation/Support
Collaborators: 50 institutions, ~300 users (>1 week)

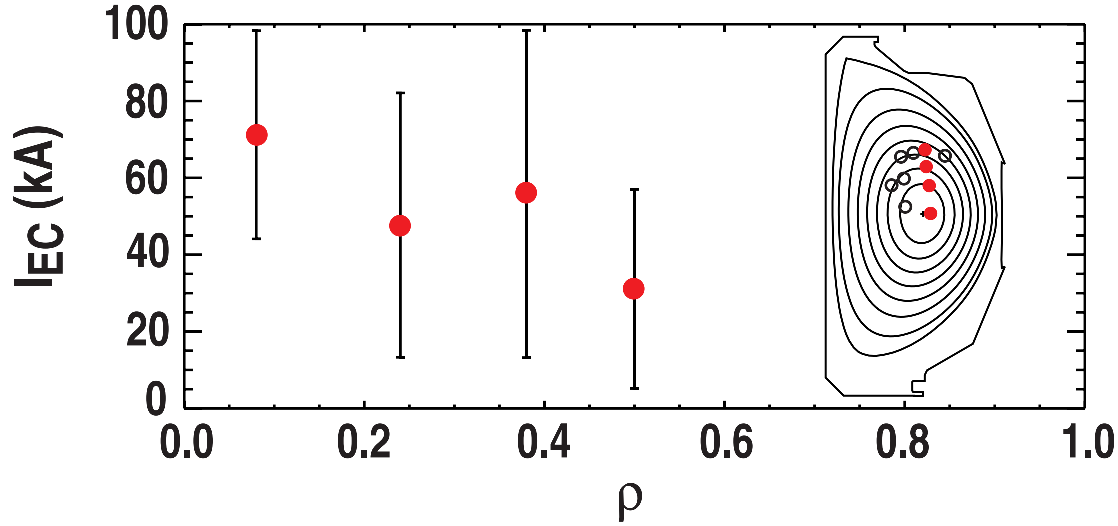
NATIONAL LABS	UNIVERSITIES	INTERNATIONAL LABS
ANL	Alaska	ASIPP (China)
INEL	Alberta	Cadarache (France)
LANL	Cal Tech	CCFM (Canada)
LLNL	Chalmers U.	Culham (England)
ORNL	Columbia U.	FOM (Netherlands)
PNL	Georgia Tech	Frascati (Italy)
PPPL	Hampton U.	Ioffe (Russia)
SNLA	Helsinki U.	IPP (Germany)
SNLL	Johns Hopkins U.	JAERI (Japan)
	Lehigh	JET (EC)
	MIT	KAIST (Korea)
	Moscow State U.	Keldysh Inst. (Russia)
	RPI	KFA (Germany)
	U. Maryland	Kurchatov (Russia)
	U. Texas	Lausanne (Switzerland)
	U. Toronto	NIFS (Japan)
	U. Wales	Troitsk (Russia)
	U. Washington	SINICA (China)
	U. Wisconsin	SWIP (China)
	UC Berkeley	Southwestern Inst. (China)
	UC Irvine	Tsukuba U. (Japan)
	UCLA	
	UCSD	

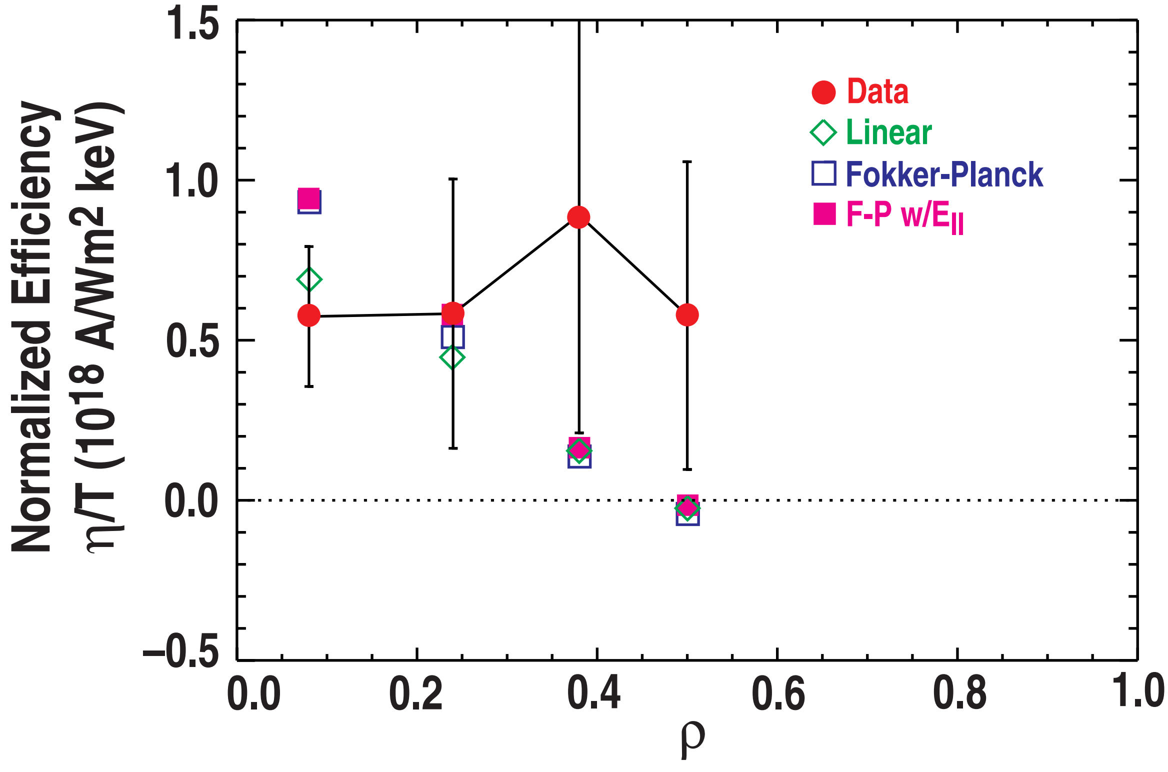
INDUSTRY COLLABS

- CompX
- CPI (Varian)
- GA
- Gycom
- Orincon

⇒ **Attributes favorable for continued fusion research at the DIII–D site**

NORMALIZED CURRENT DRIVE EFFICIENCY DOES NOT DROP WITH RADIUS AS EXPECTED FROM THEORY





DIII–D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

259-98 jy

GENERAL ATOMICS

CQL3D: 3 D Bounce-Averaged Fokker-Planck Code for ECH/LH/FW/NBI

Solves the coupled equations: for $f_0(v_{\parallel 0}, v_{\perp 0}, \rho; t)$ — $v_{\parallel 0}, v_{\perp 0}$: constants of collisionless motion

(1) $$\frac{\partial}{\partial t}(\lambda f_0) = \frac{\partial}{\partial \underline{u}_0} \cdot \left[\underline{\Gamma}_{\text{DC}} + \underline{\Gamma}_{\text{RF}} + \underline{\Gamma}_{\text{coll}} \right] + R(f_0) + S_{\text{NB}}$$

DC ELECTRIC FIELD
RF QL OPERATOR
NL COLLISIONS (FP)
RADIAL DIFFUSION AND CONVECTION
NB DEPOSITION

(2) RF energy equation, along rays:

$$\nabla \cdot \left(\underline{v}_{\text{group}}\, \mathcal{E} \right) = -P_{\text{absorbed}}$$
$$= -\int \underline{du}\, (\gamma - 1)\, mc^2\, Q(f_0)$$

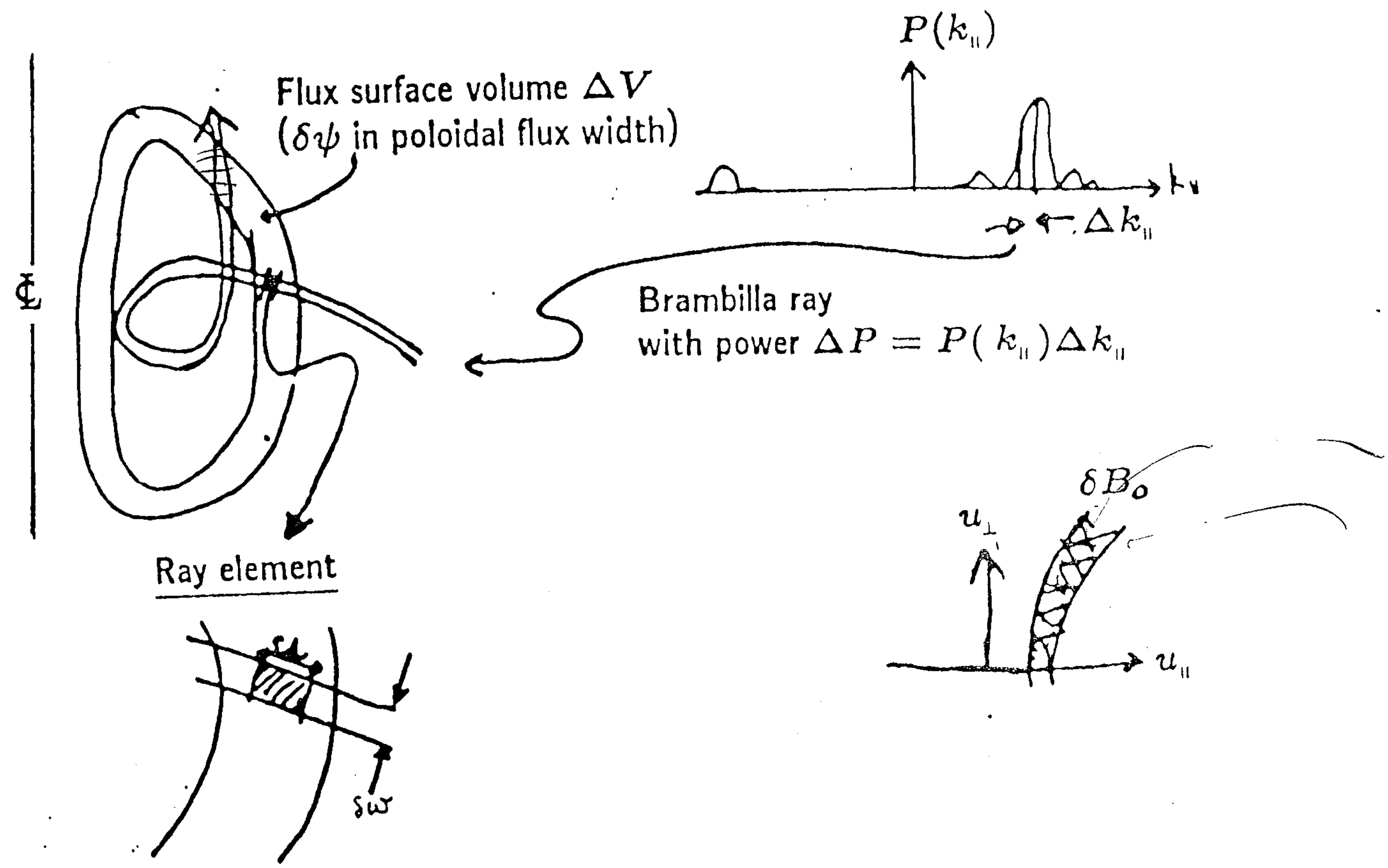
QL OPERATOR

(3) NBI Source (FREYA)

(4) Equilibrium Equation

$$\nabla^* \Psi = \mu_0 J_\phi$$

Numerical Approach to B_0 (RF QL Operator)



$$\delta B_0 = \frac{1}{\Delta V} \int dV \oint \frac{d\ell_B}{|u_\parallel|}\, u^2 \cos^2\theta\, D_\parallel$$

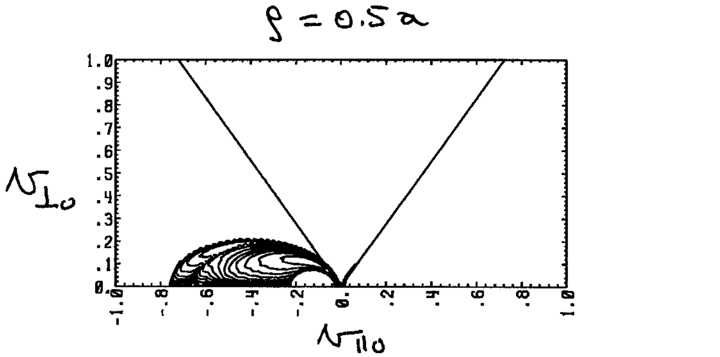
↑ Local QL diffusion coefficient

$$D_\parallel = \frac{\pi e^2}{2\, m_e^2} \left(\frac{n_\parallel u}{\gamma c}\right)^2 \frac{\gamma}{|u_\parallel|} \left| u_\parallel J_0\left(\frac{k_\perp u_\perp}{\omega_{ce}}\right) E_z + i u_\perp J_1\left(\frac{k_\perp u_\perp}{\omega_{ce}}\right) E_y \right|^2$$

$$P_{abs} = \int d^3v\, (\gamma - 1)\, mc^2\, \frac{\partial f}{\partial t}\bigg|_{QL}$$

Bounce-Avg'd Quasilinear Diffusion Coeff

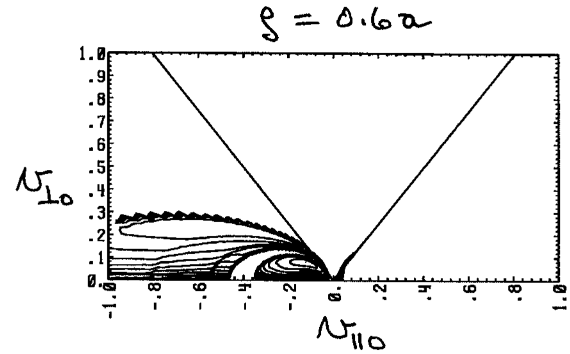
$\rho = 0.5a$



time step (n) is 1 time= 0.100000E+01 secs
r/a= 0.500000E+00 radial position (r) = 0.42

Contours of the rf (v,v) diffusion coefficient, urfb
Flux surface number 10
mode=1

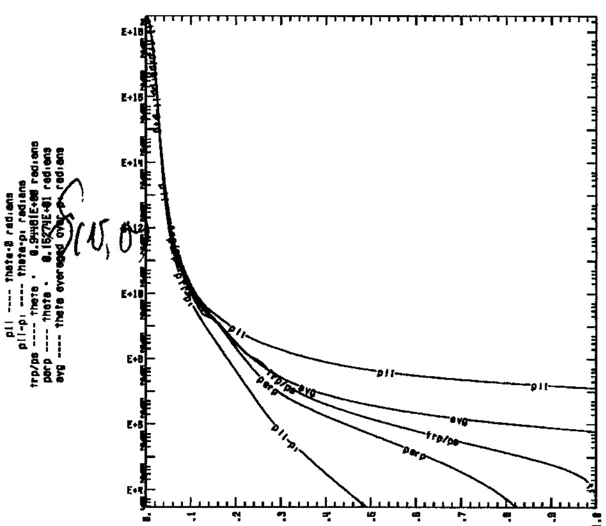
$\rho = 0.6a$



time step (n) is 1 time= 0.100000E+01 secs
r/a= 0.600000E+00 radial position (r) = 0.50

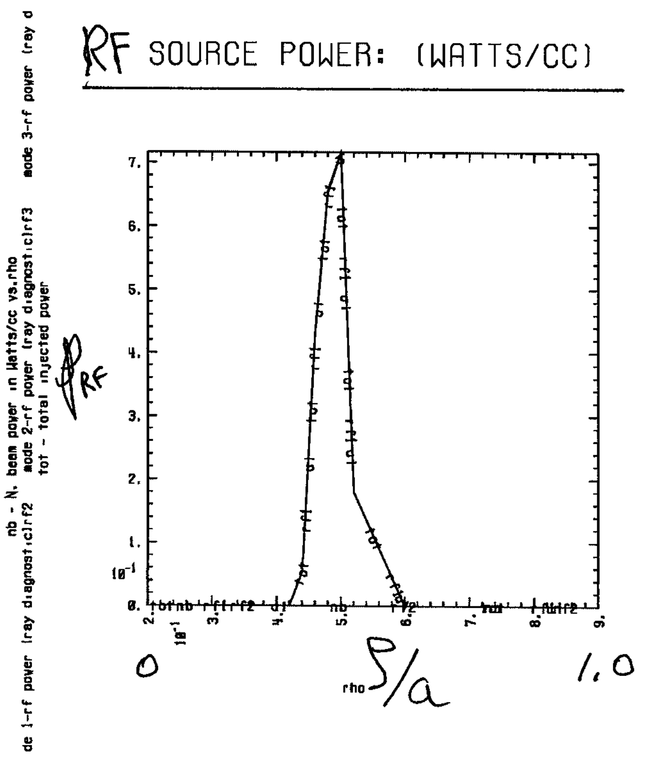
Contours of the rf (v,v) diffusion coefficient, urfb
Flux surface number 12
mode=1

electron dist^n fct^n at $\rho = 0.5a$

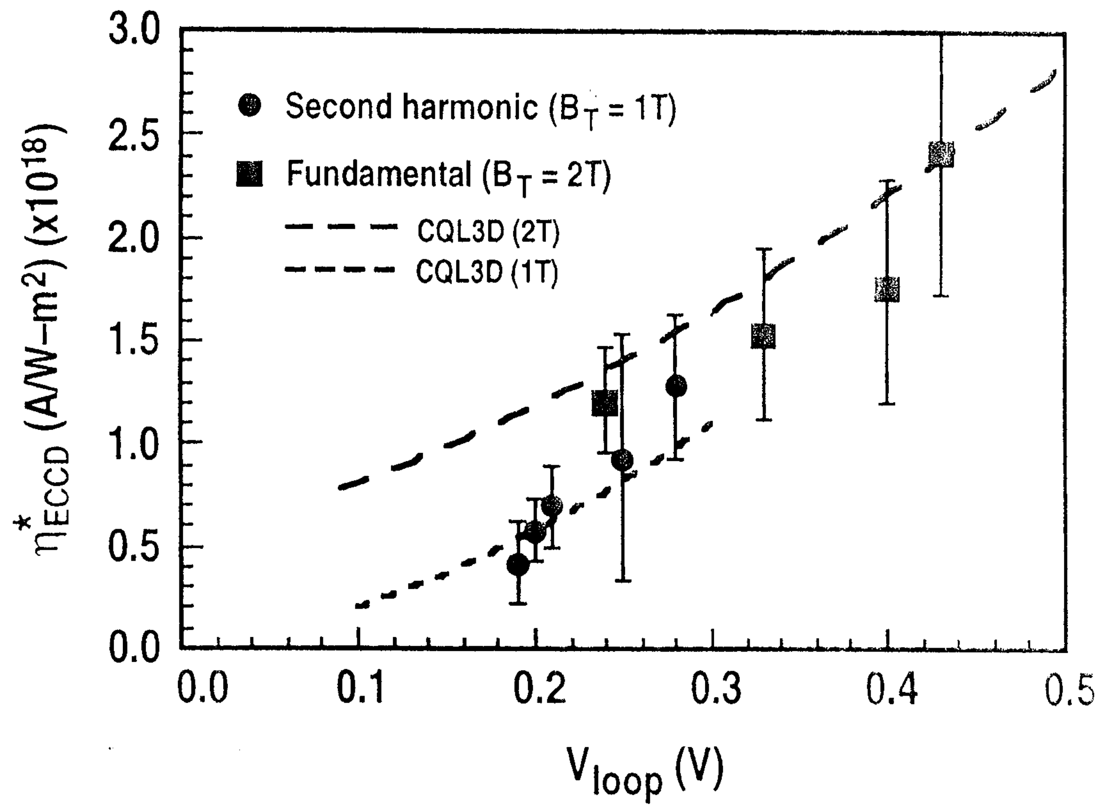


Distribution function vs. velocity for some angles
species number = 1
time step (n) is 10 time= 0.100000E+02 secs
r/a= 0.500000E+00 radial position (r) = 0.421192E+02 cm

RF SOURCE POWER: (WATTS/CC)



EXPERIMENTAL DEPENDENCE OF E_{dc} IS MODELED WELL BY CQL3D

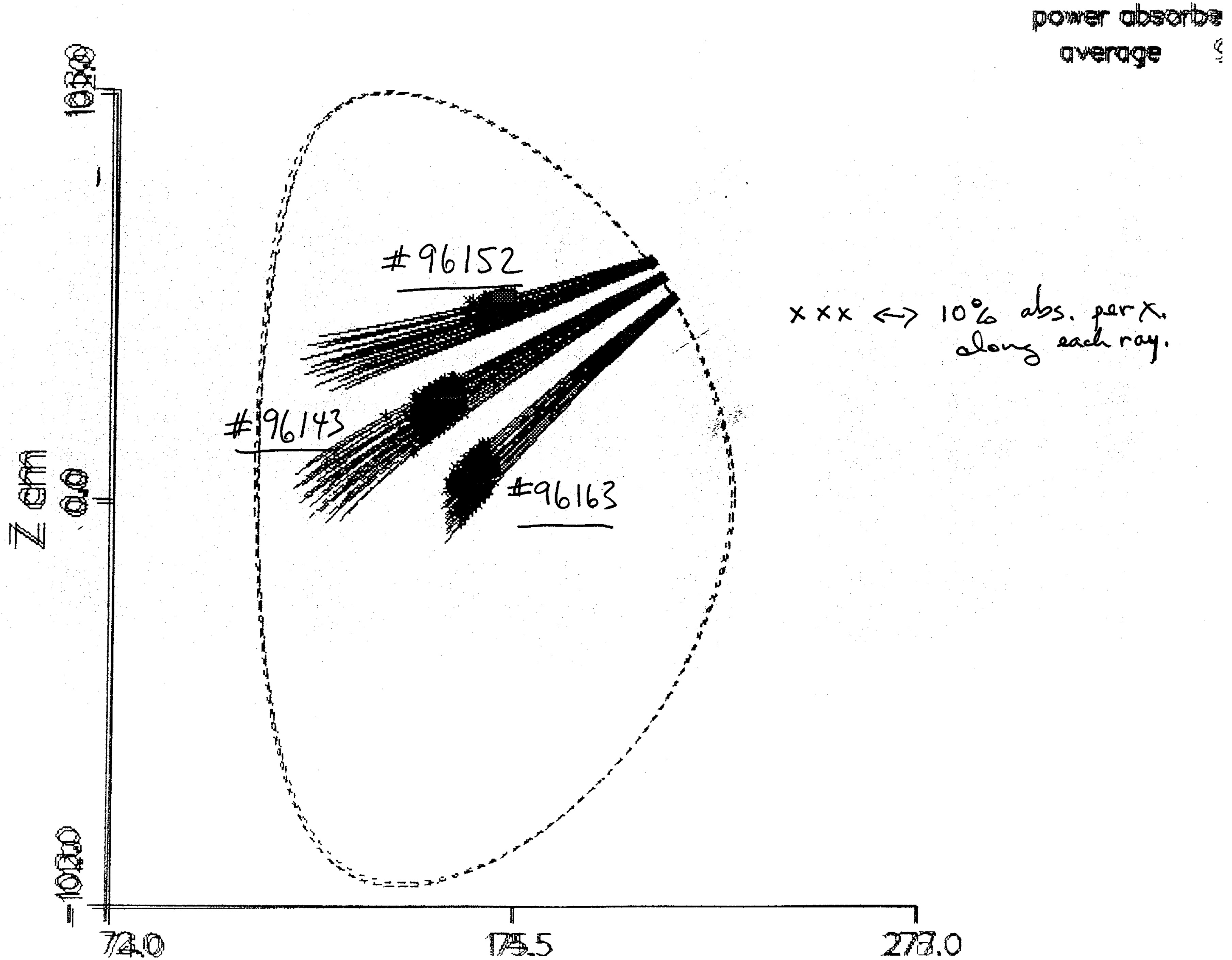


- $\eta^* = \dfrac{n_e I_{rf} R_m}{P_{rf}}$ with finite E_{dc}
- $E_{dc} = V_{loop}/2\pi R_m$

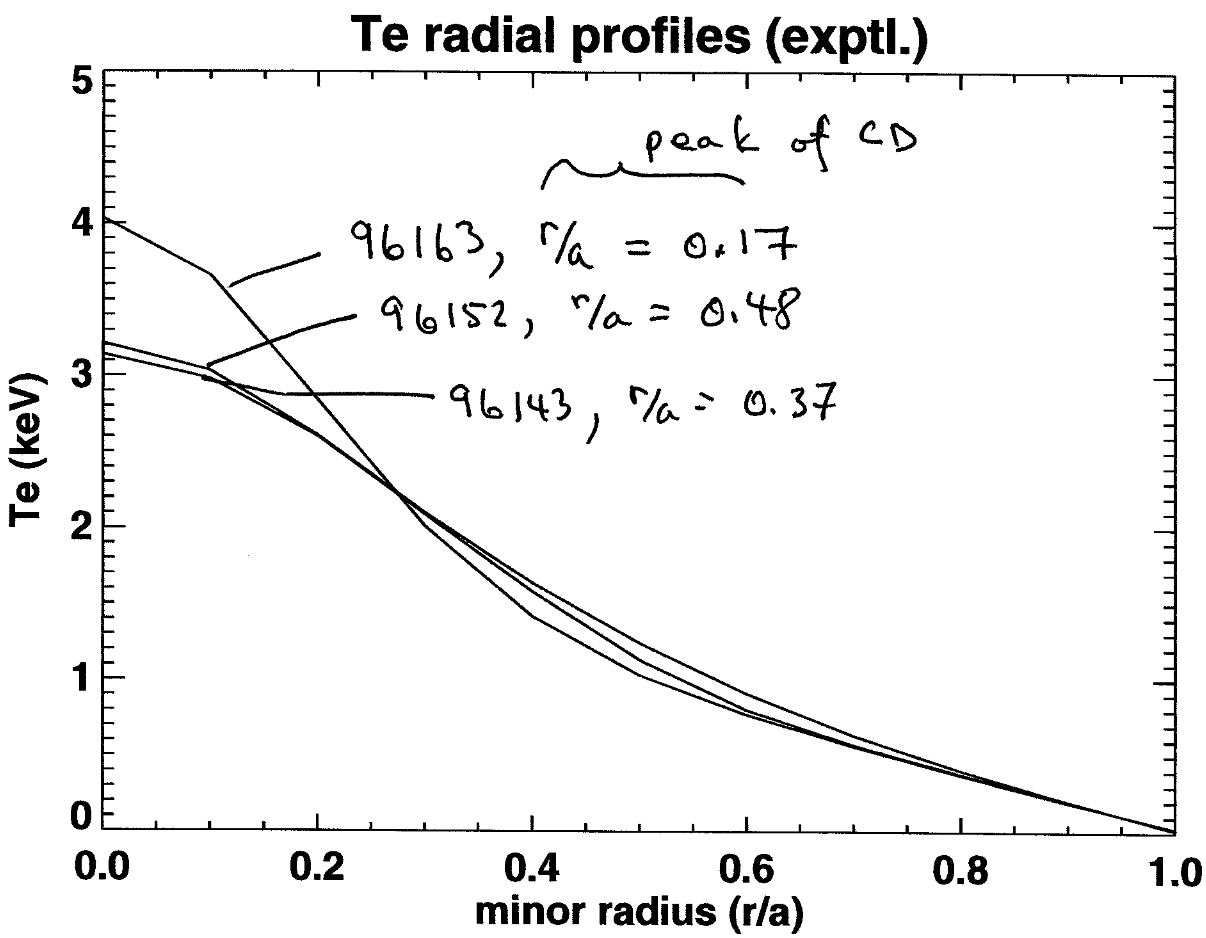
R.A. James, et al., "Electron Cyclotron Current Drive Experiments in the DIII–D Tokamak," Phys. Rev. A 45, 8783 (1992).

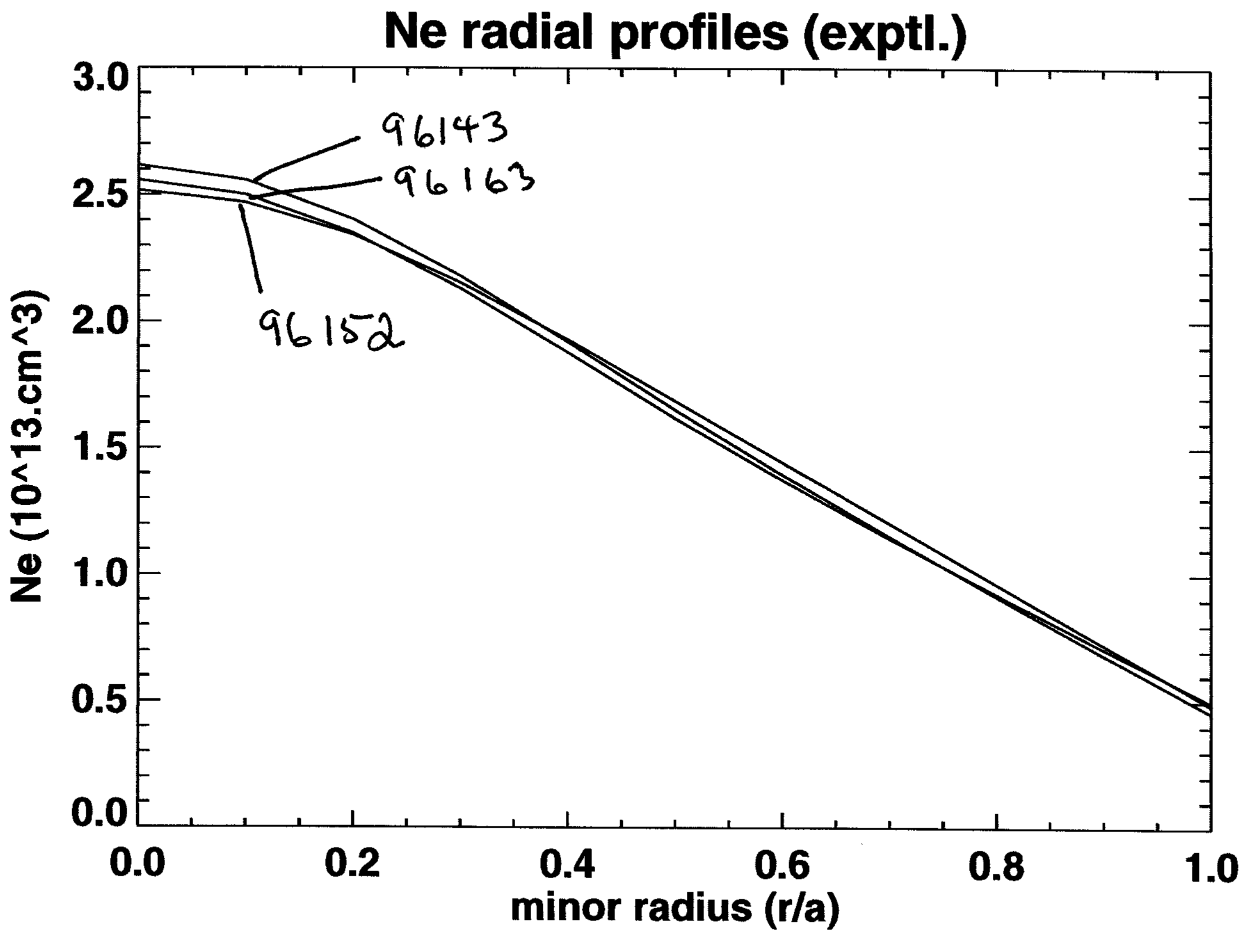
C.C. Petty, et al., "Fast Wave and Electron Cyclotron Current Drive in the DIII–D Tokamak," accepted for publication in Nucl. Fusion

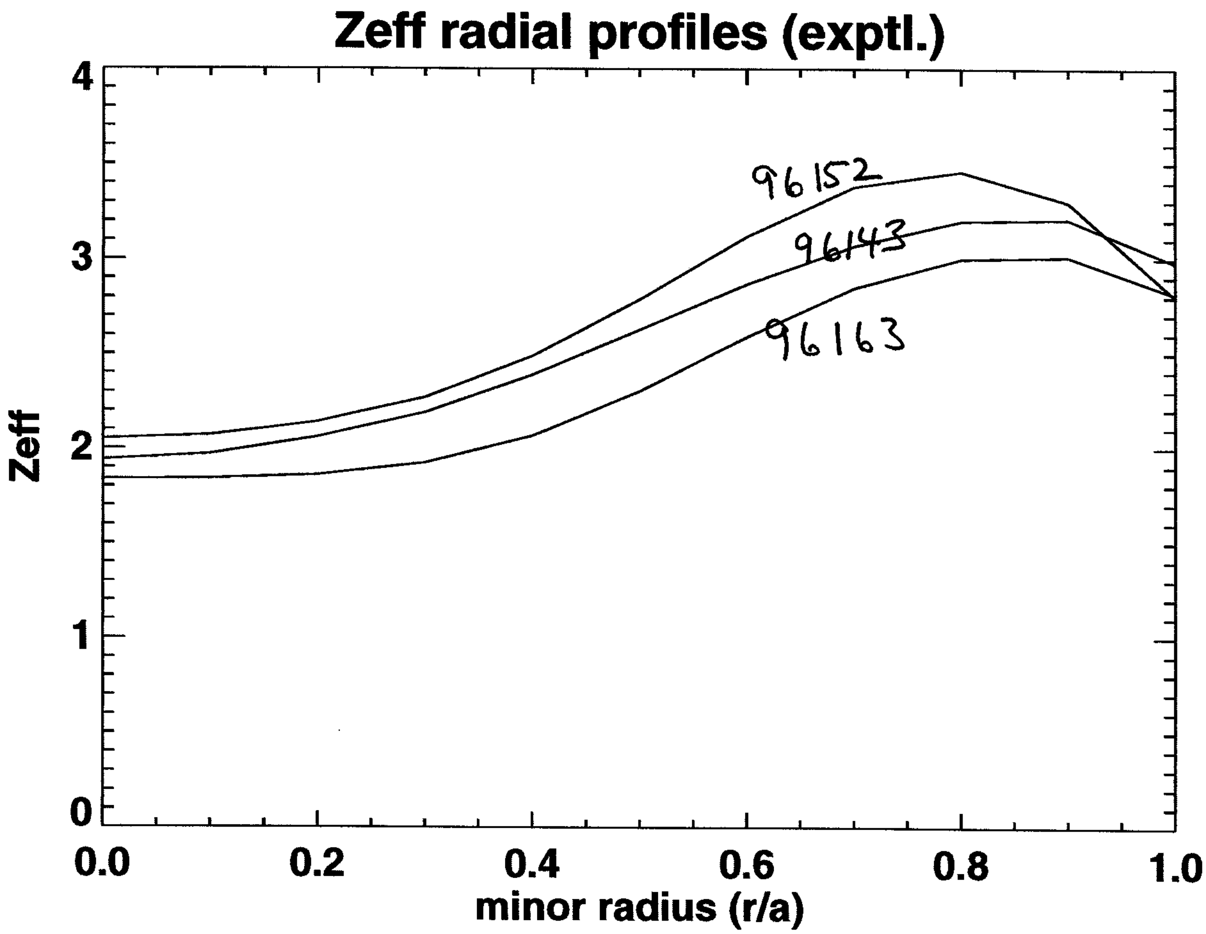
DIII-D Shot Analysis with ECCD at $\rho/a = 0.17, 0.37$, and 0.48 give nominal parameters for this study



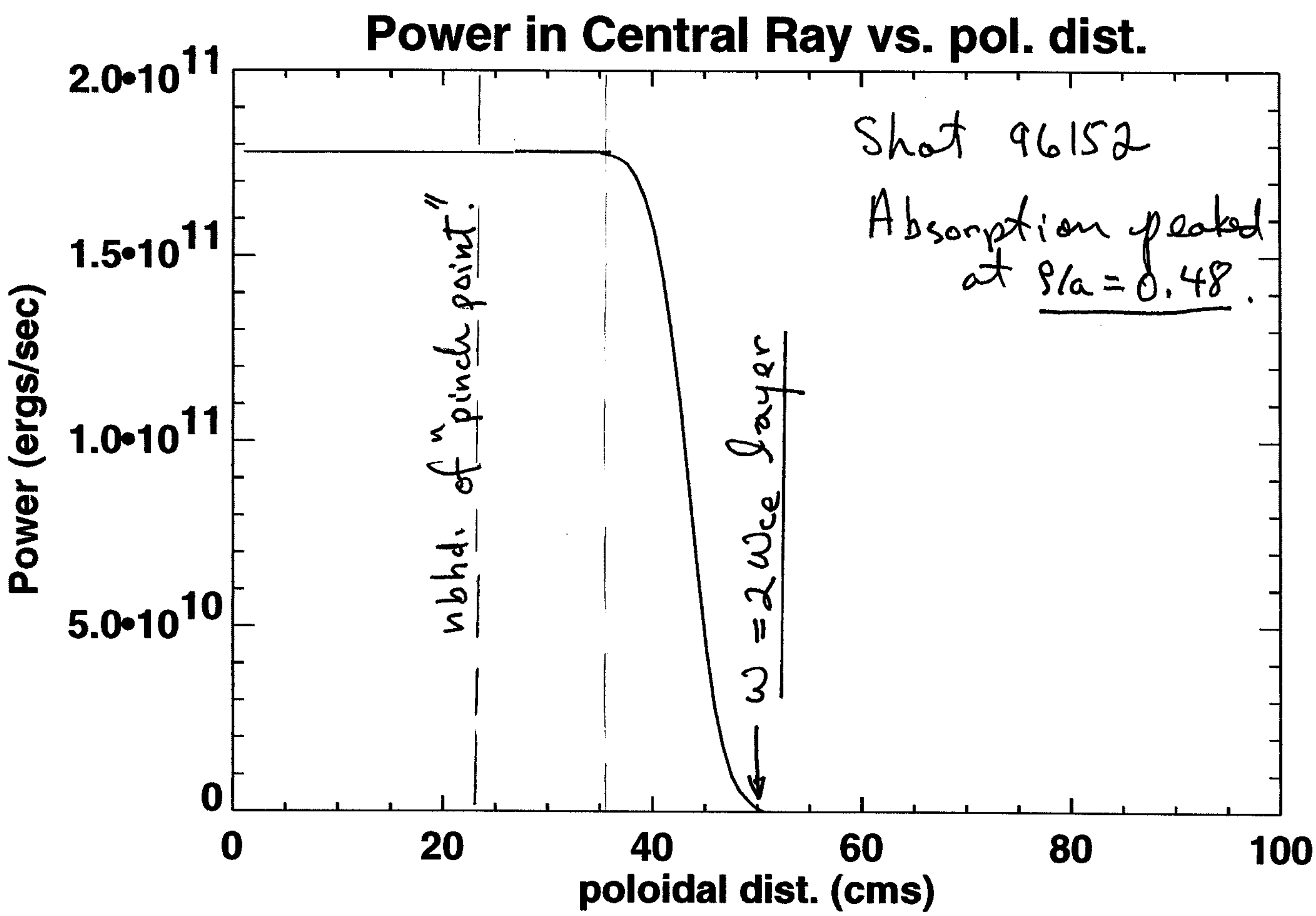
power absorbe
average
Z cm
102.0
0.0
-102.0
74.0
175.5
277.0
#96152
#96143
#96163
x x x <-> 10% abs. per x.
along each ray.


Te radial profiles (exptl.)
peak of CD
96163, r/a = 0.17
96152, r/a = 0.48
96143, r/a = 0.37
Te (keV)
minor radius (r/a)
0
1
2
3
4
5
0.0
0.2
0.4
0.6
0.8
1.0

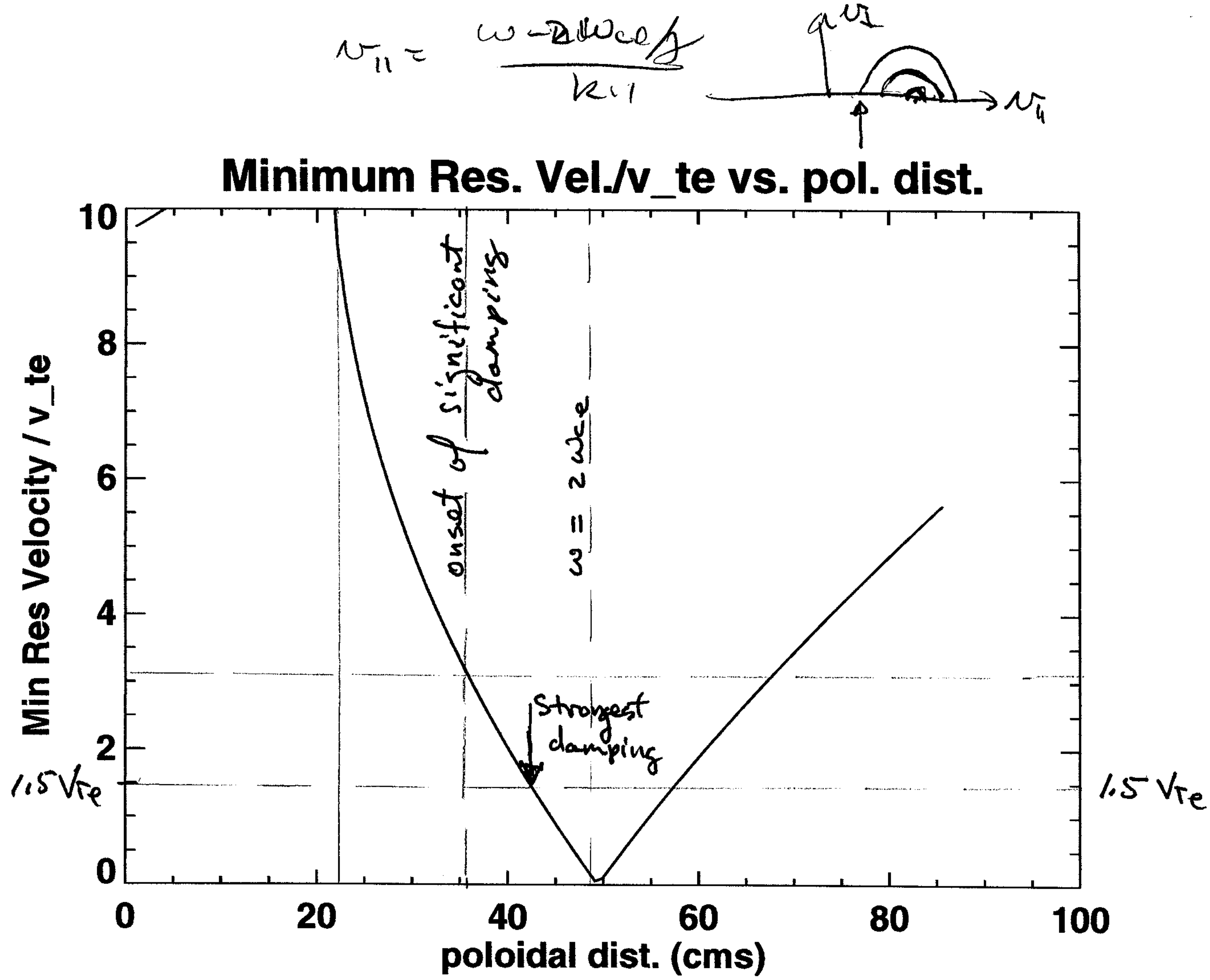

Ne radial profiles (exptl.)
Ne (10^13.cm^3)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
minor radius (r/a)
96143
96163
96152

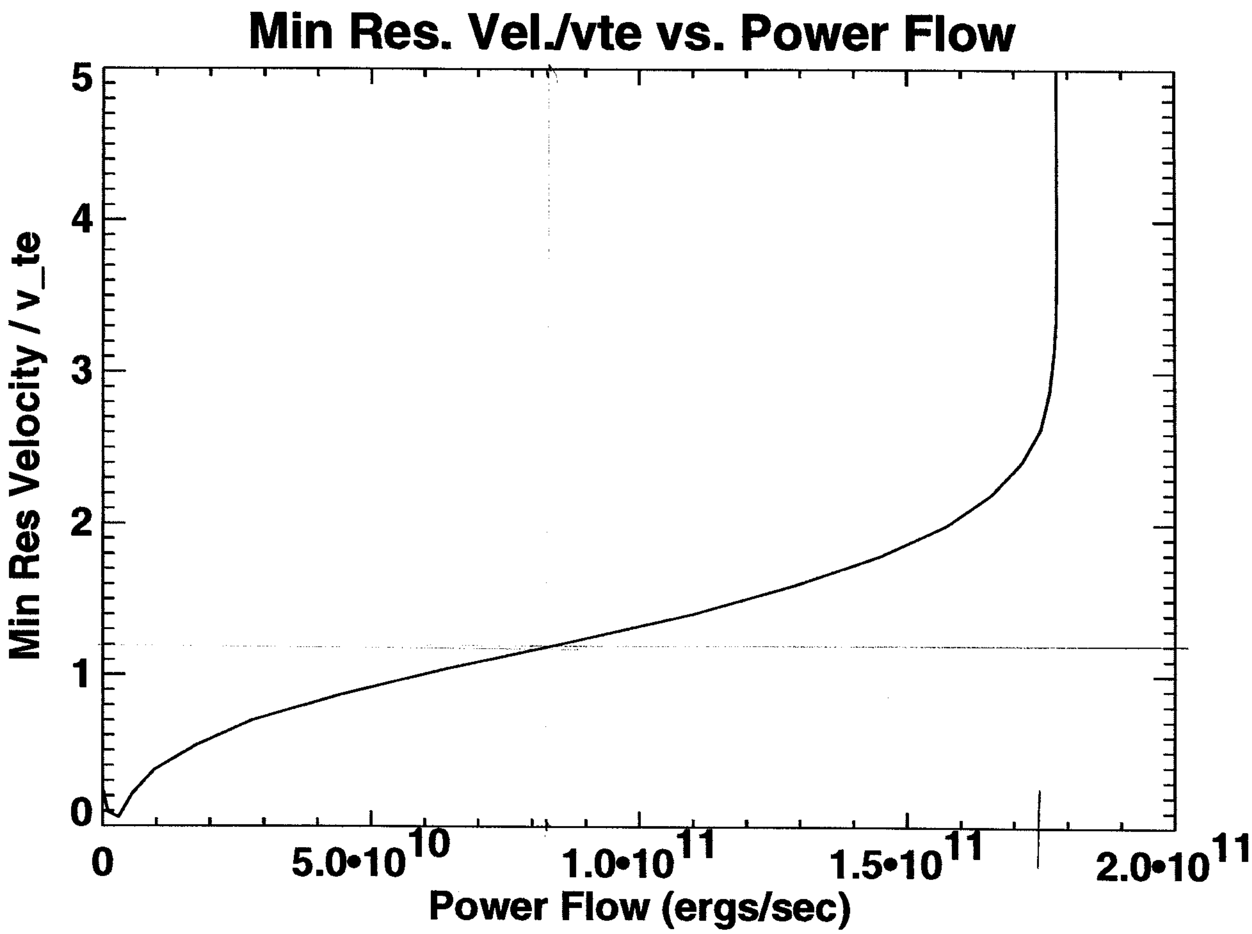

Zeff radial profiles (exptl.)
Zeff
minor radius (r/a)
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
96152
96143
96163

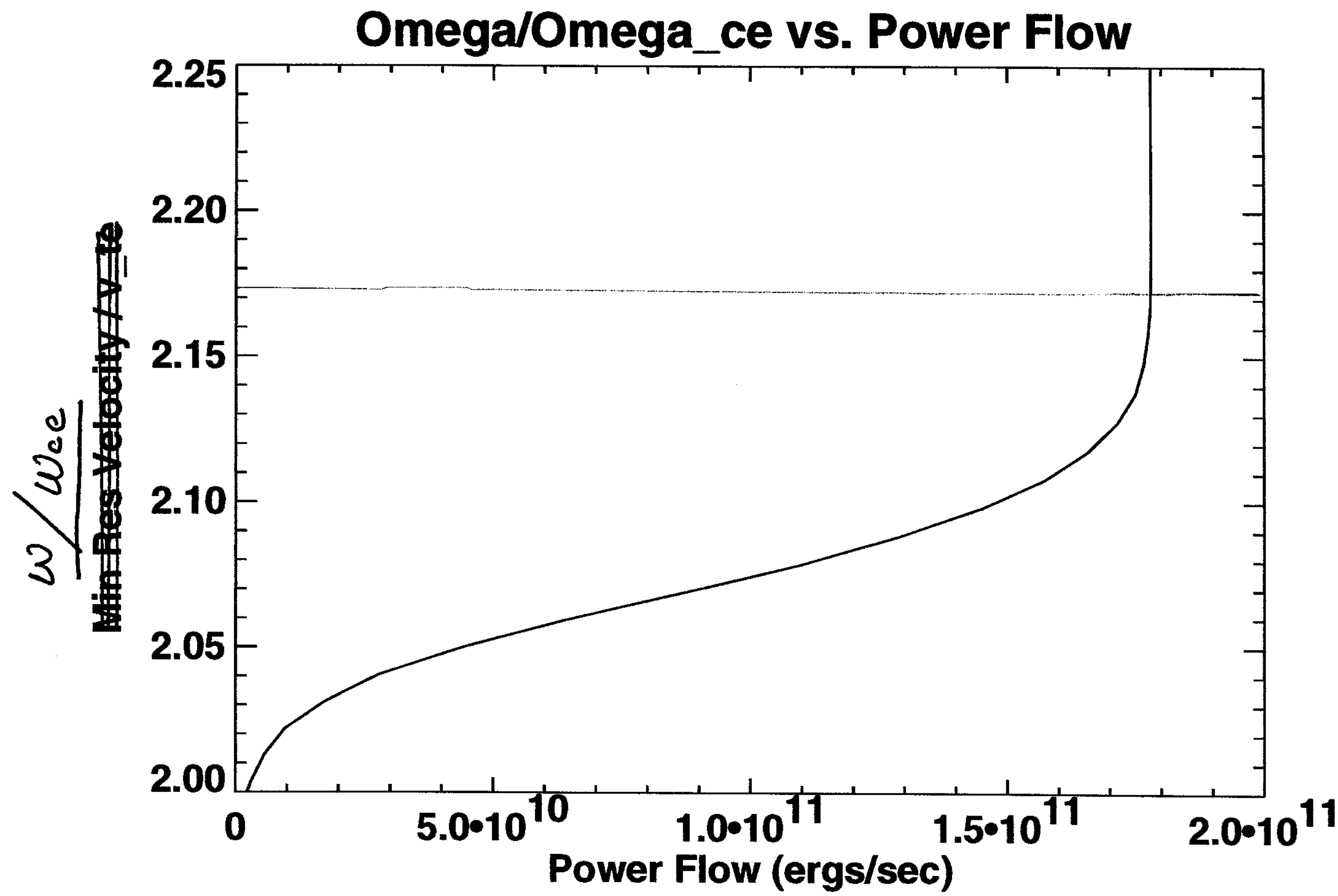
Examination of ray trajectory data shows that for $\rho/a \approx 0.5$ damping is occuring on electrons with velocity in the neighborhood of v_{Te}.



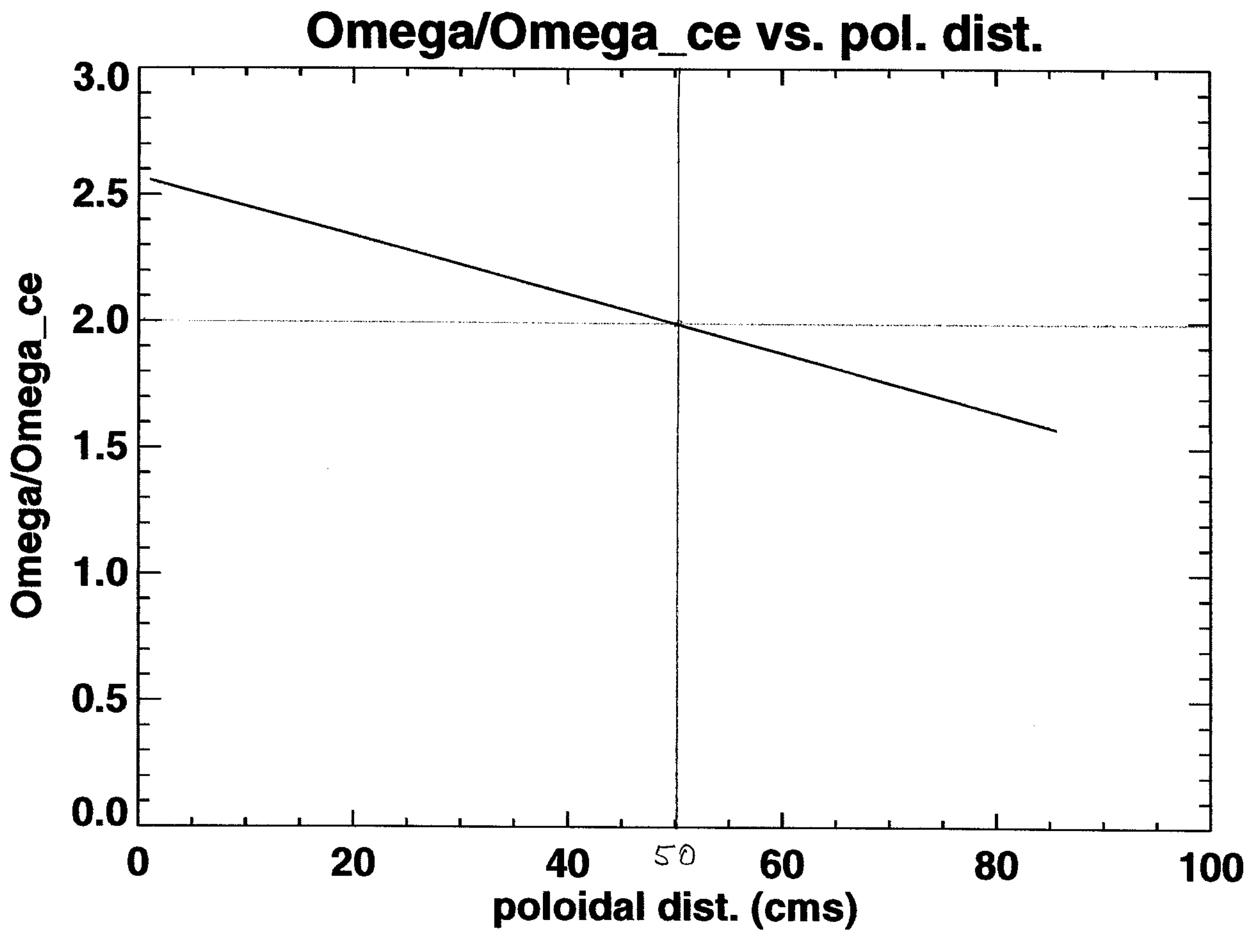
Power in Central Ray vs. pol. dist.
Power (ergs/sec)
2.0•10^11
1.5•10^11
1.0•10^11
5.0•10^10
0
0
20
40
60
80
100
poloidal dist. (cms)
Shot 96152
Absorption peaked at ρ/a = 0.48.
nbhd. of "pinch point."
ω = 2ωce layer

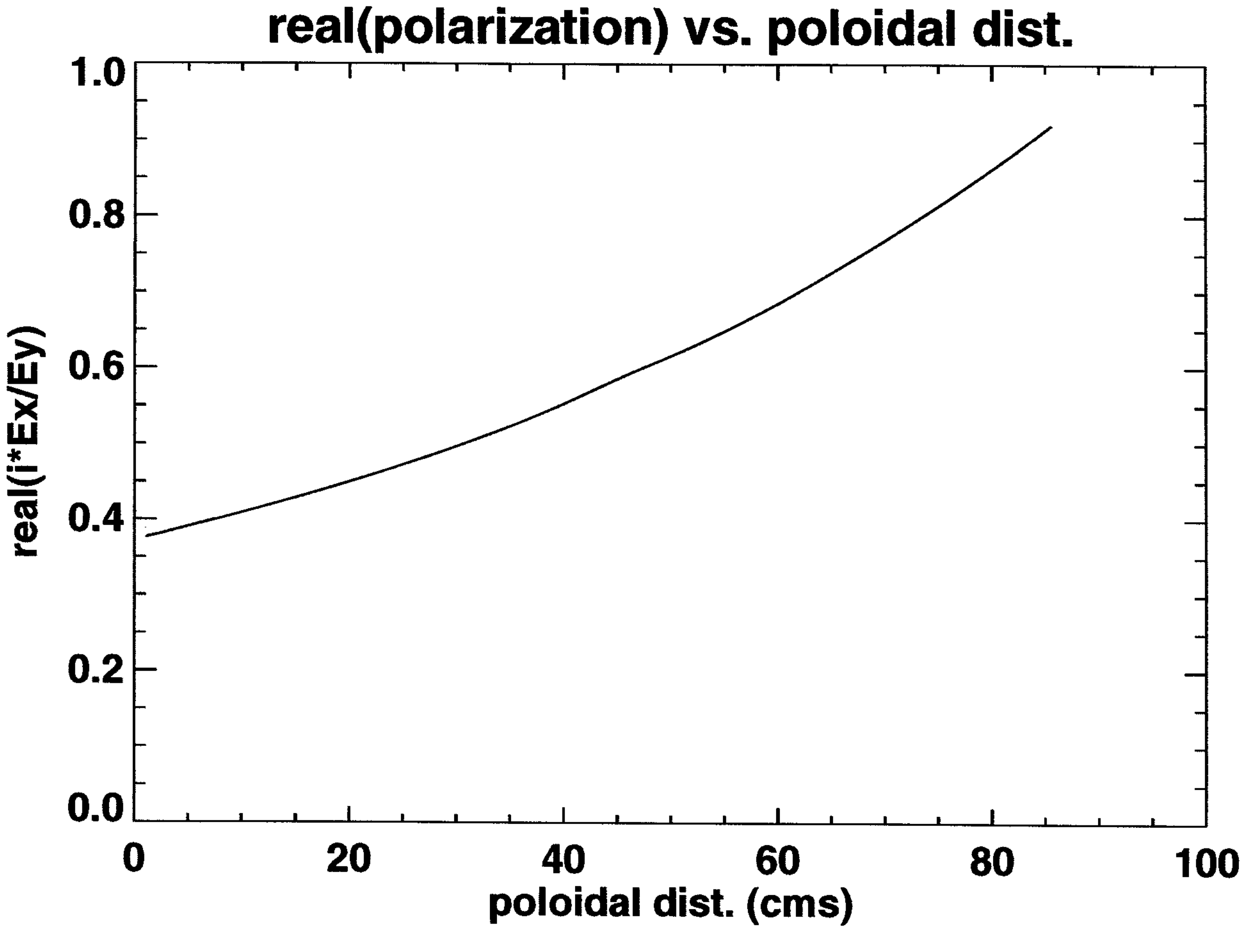

Minimum Res. Vel./v_te vs. pol. dist.
Min Res Velocity / v_te
poloidal dist. (cms)
0
20
40
60
80
100
2
4
6
8
10
onset of significant damping
ω = 2ωce
Strongest damping
1.5 Vte
1.5 Vte

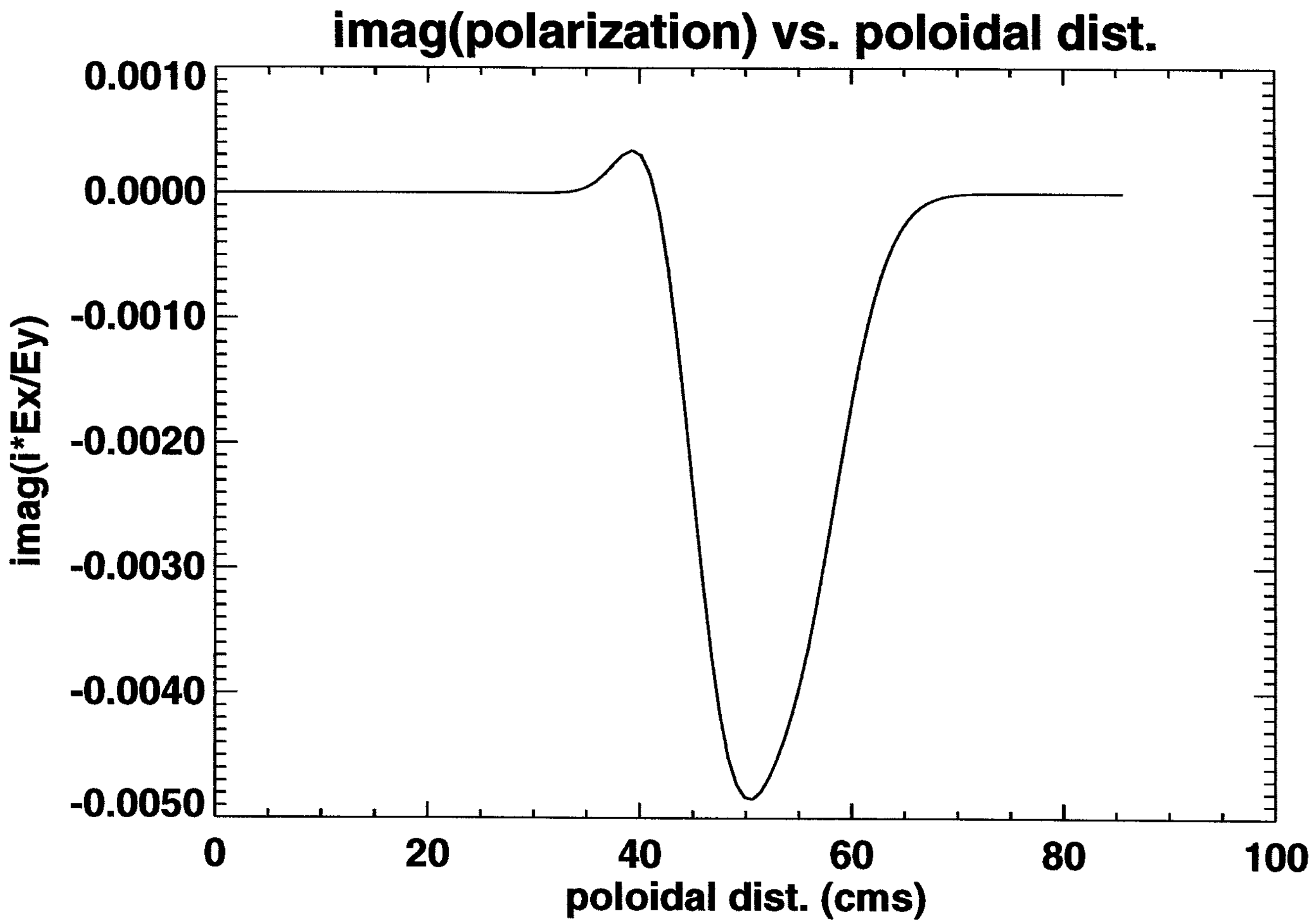

Min Res. Vel./vte vs. Power Flow
Min Res Velocity / v_te
Power Flow (ergs/sec)
0
1
2
3
4
5
0
5.0•10^10
1.0•10^11
1.5•10^11
2.0•10^11



Omega/Omega_ce vs. Power Flow
2.25
2.20
2.15
2.10
2.05
2.00
Min Res Velocity / v_te
ω/ω_ce
0
5.0•10^10
1.0•10^11
1.5•10^11
2.0•10^11
Power Flow (ergs/sec)


Omega/Omega_ce vs. pol. dist.
Omega/Omega_ce
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
50
60
80
100
poloidal dist. (cms)

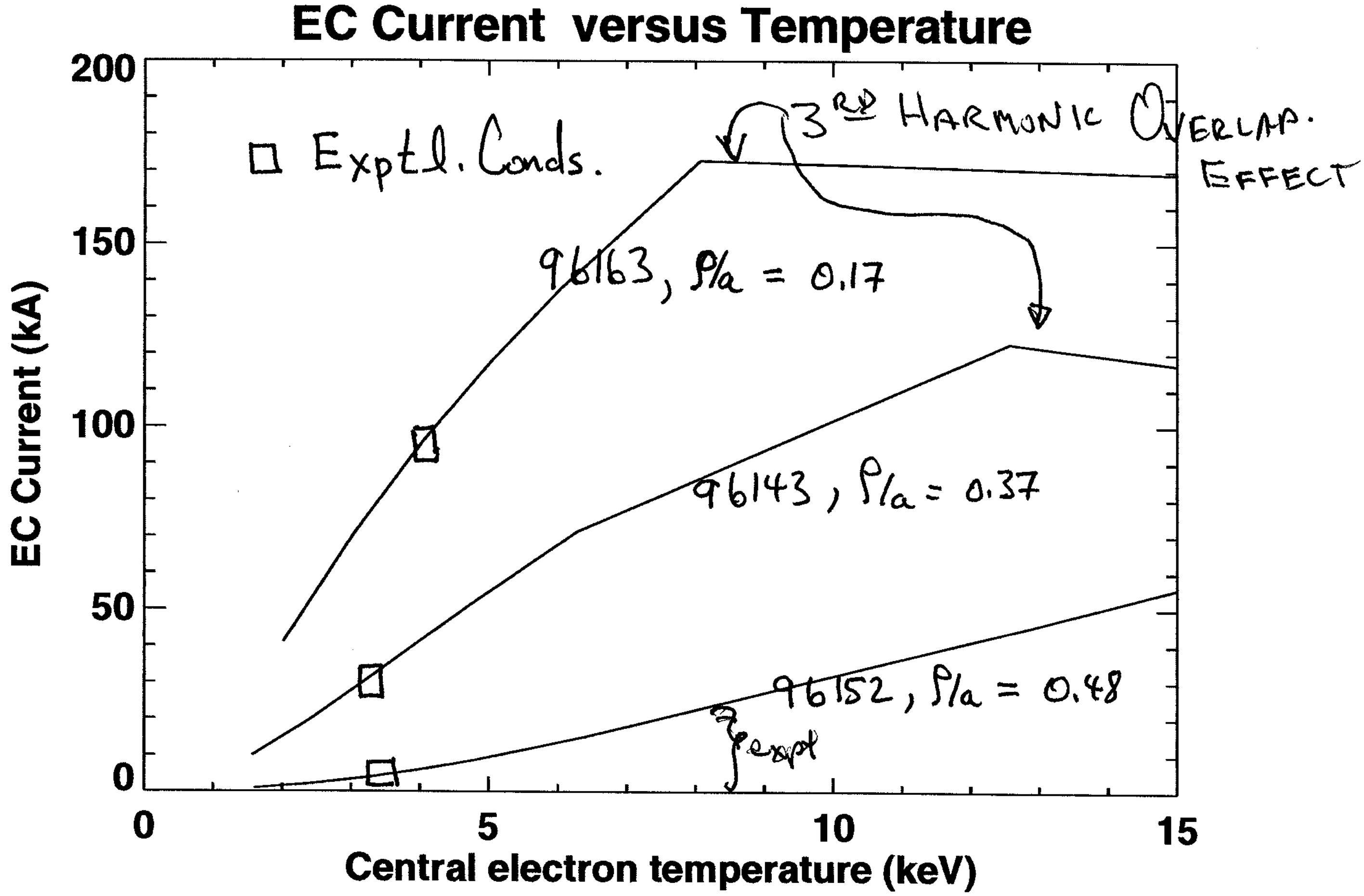

real(polarization) vs. poloidal dist.
1.0
0.8
0.6
0.4
0.2
0.0
real(i*Ex/Ey)
0
20
40
60
80
100
poloidal dist. (cms)



imag(polarization) vs. poloidal dist.
0.0010
0.0000
-0.0010
-0.0020
-0.0030
-0.0040
-0.0050
imag(i*Ex/Ey)
0
20
40
60
80
100
poloidal dist. (cms)

Smooth Variation of the Calc'd ECCD with Profile Variations

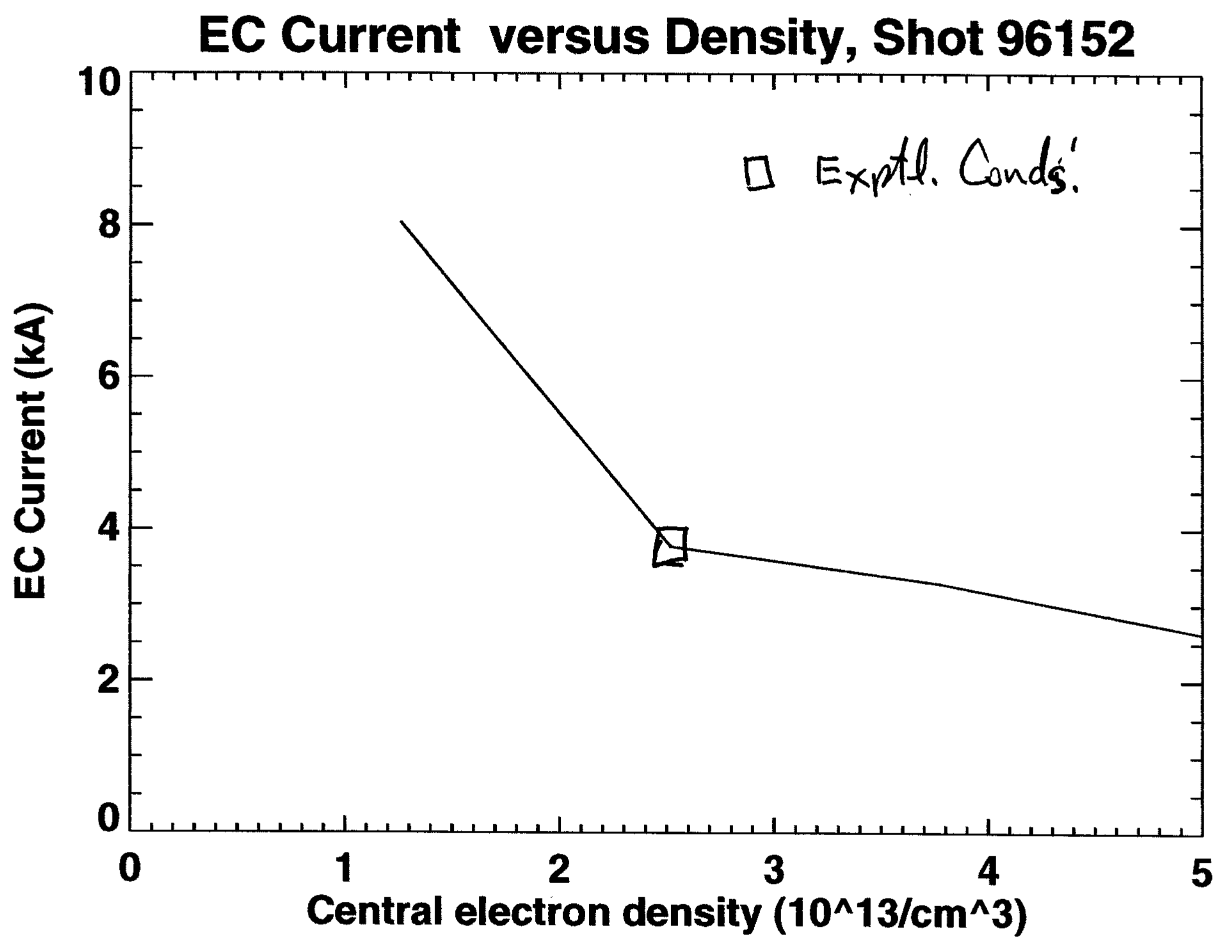
$\Longrightarrow$ Reasonable Profile Variations Cannot Explain High Off-Axis ECCD Efficiency.



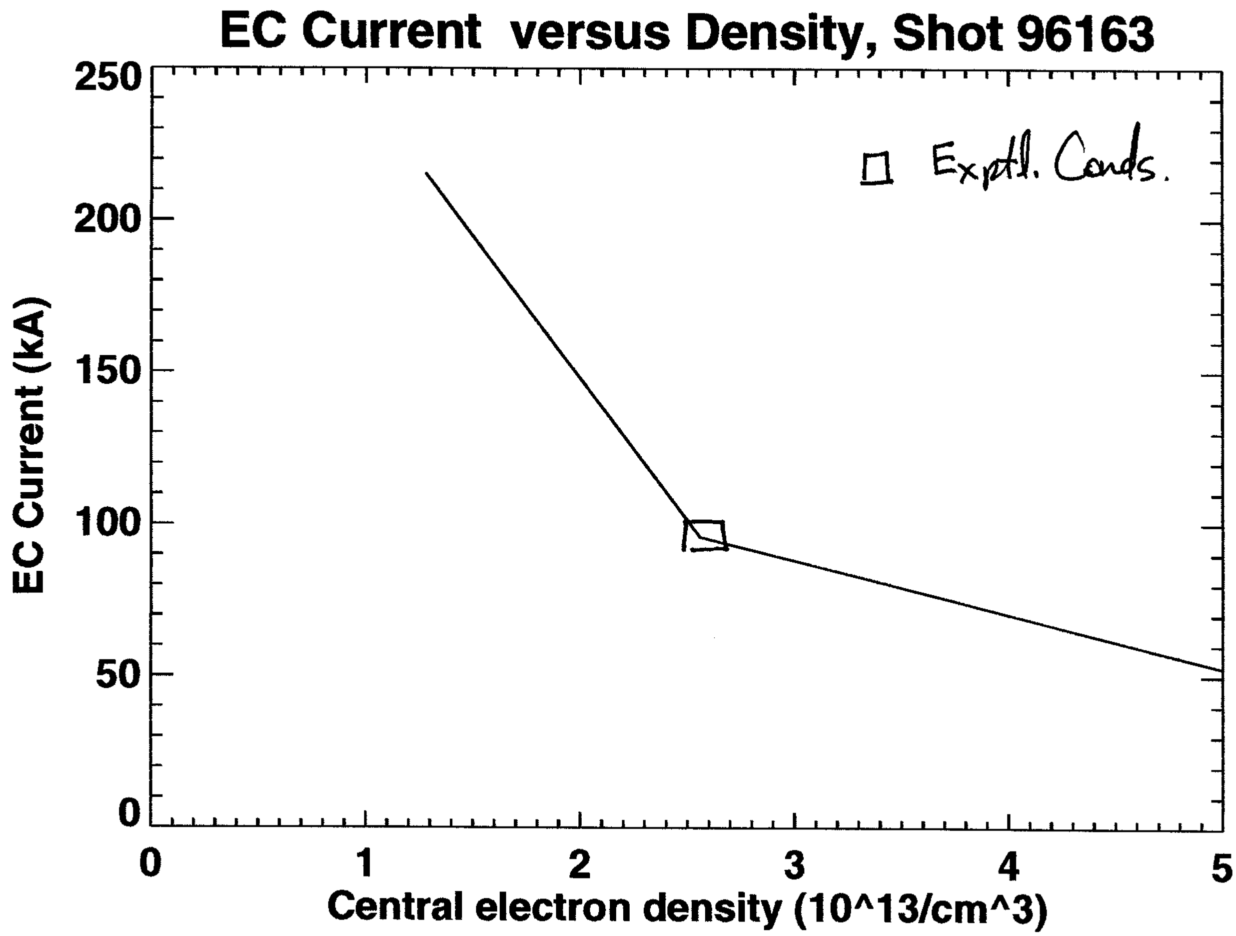
$P_{EC,96163}$ = 1.08 MW, n_{eo} = 2.56, T_{eo} = 4.03

$P_{EC,96143}$ = 0.99 MW, n_{eo} = 2.62, T_{eo} = 3.10

$P_{EC,96152}$ = 1.04 MW, n_{eo} = 2.34, T_{eo} = 3.21

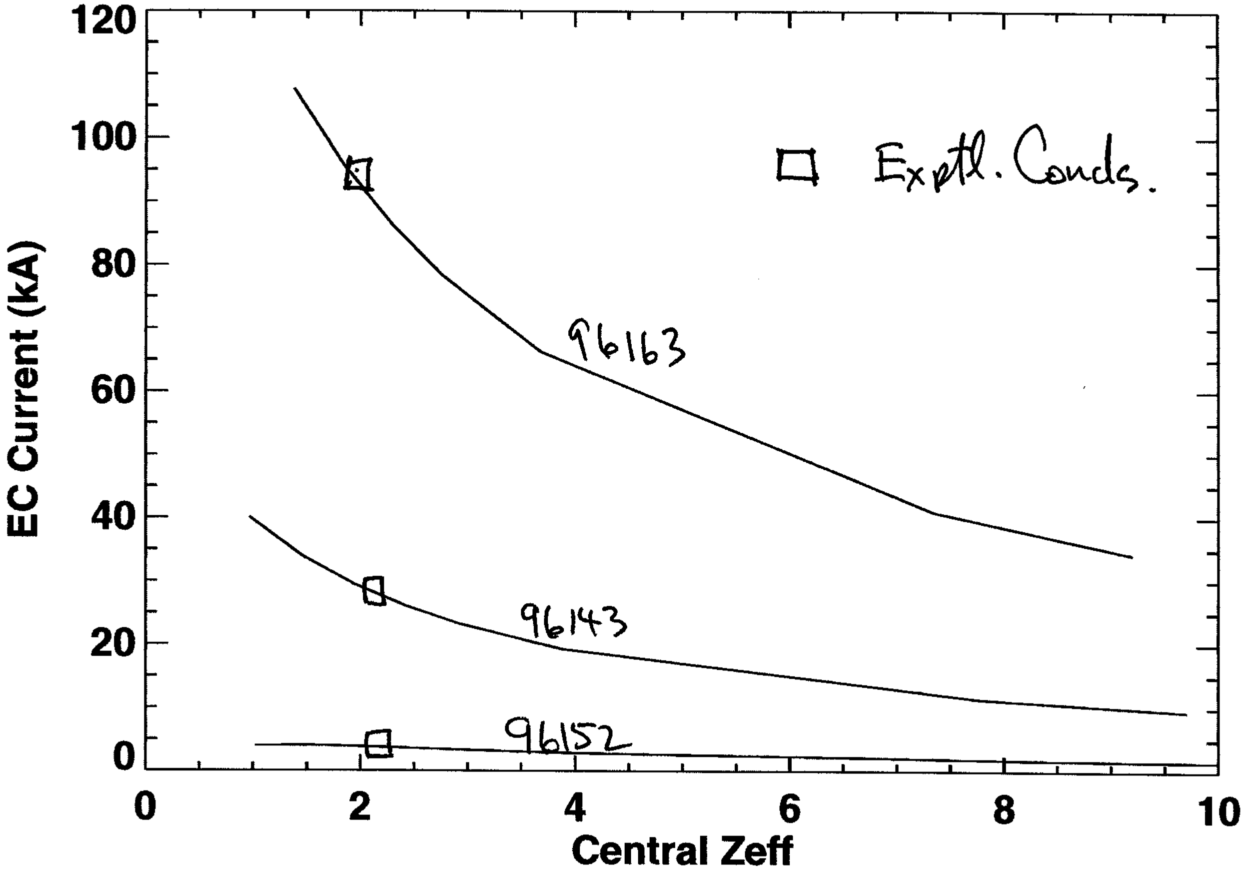


EC Current versus Density, Shot 96152
EC Current (kA)
Central electron density (10^13/cm^3)
0
2
4
6
8
10
0
1
2
3
4
5
Exptl. Conds.



EC Current versus Density, Shot 96163
EC Current (kA)
Central electron density (10^13/cm^3)
250
200
150
100
50
0
0
1
2
3
4
5
□ Exptl. Conds.

EC Current versus Zeff

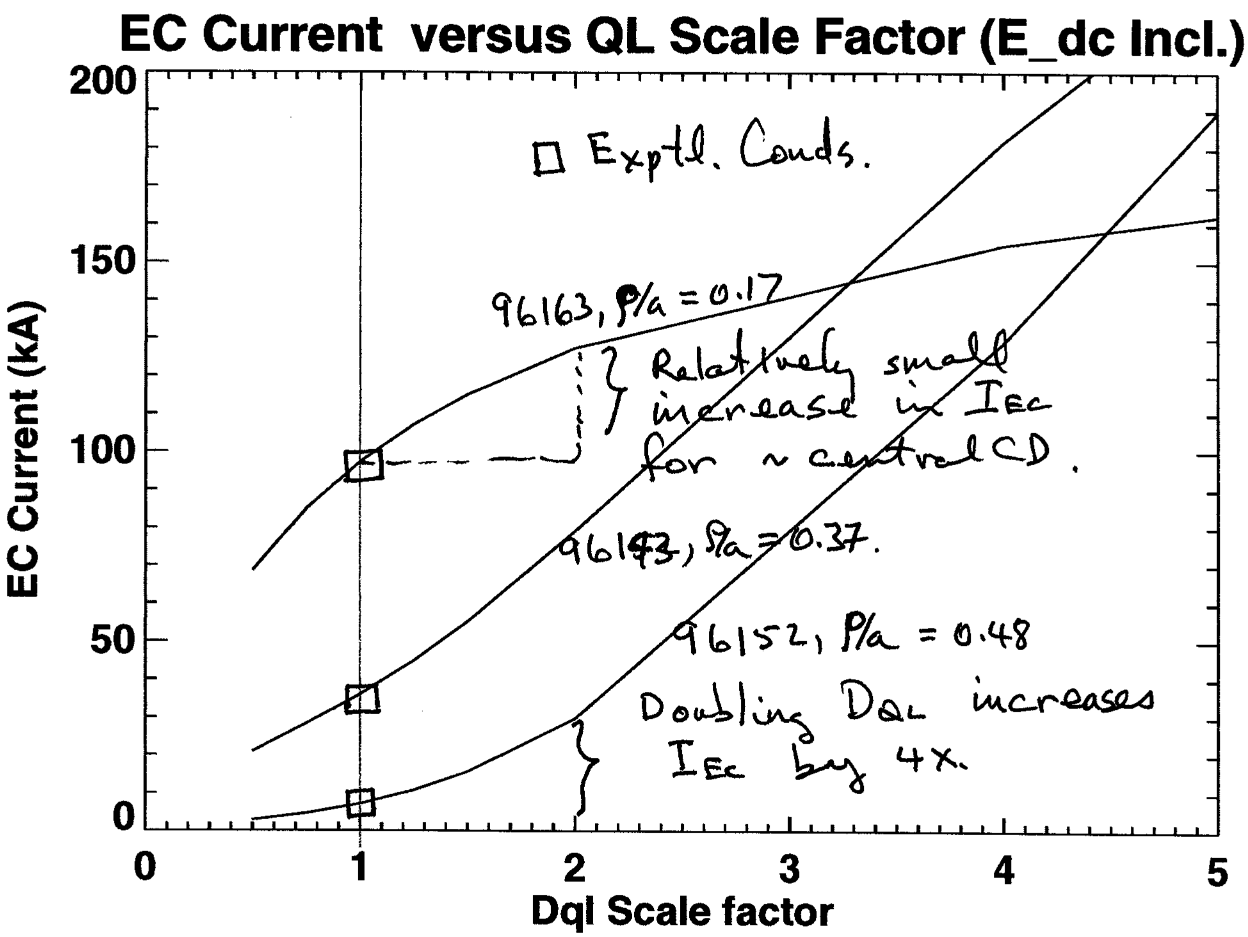


Strong Variation of ECCD Effic. with ad Hoc D_{QL} Multiplier

(particularly at $\rho/a \sim 0.5$)

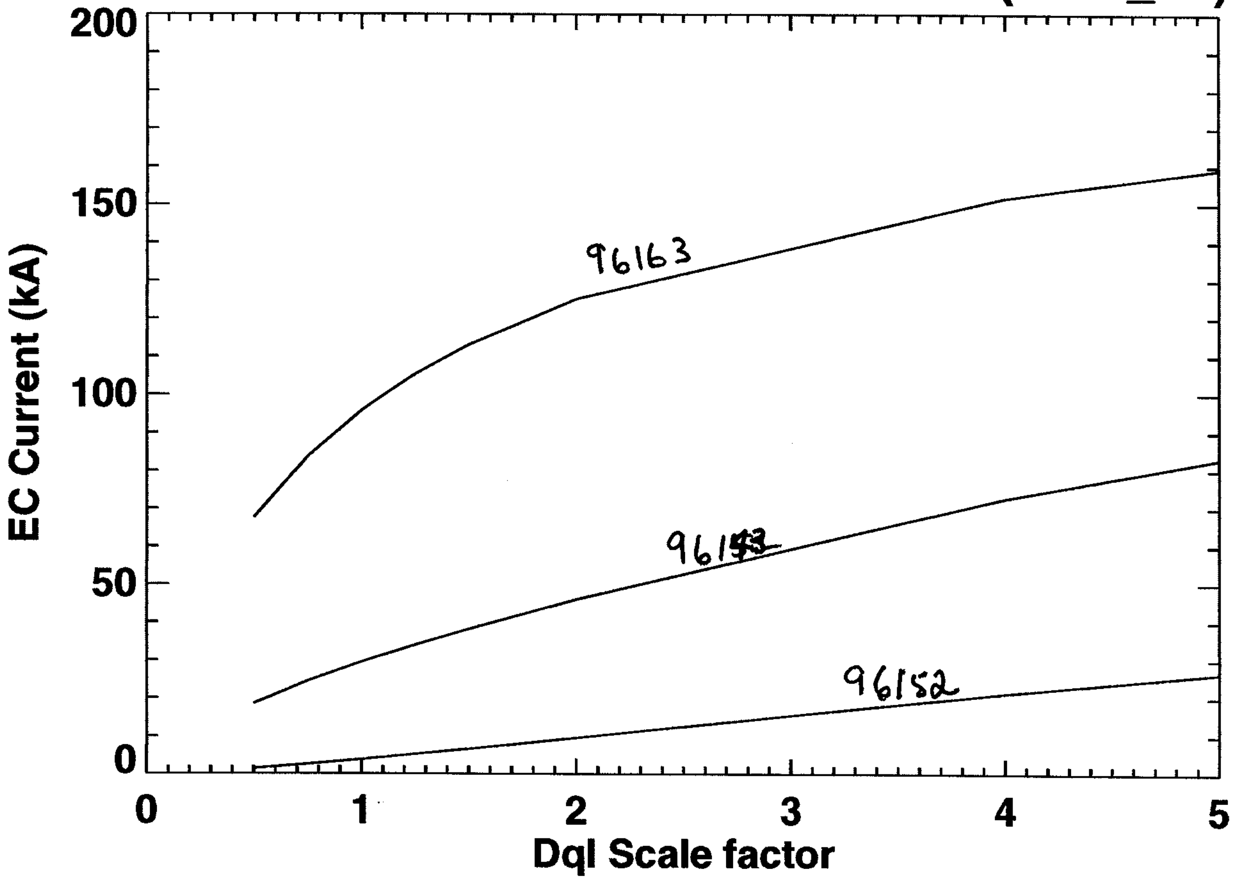
$\Longrightarrow$ ("Small") Refinement of QL Theory

May Explain High Off-Axis Efficiency.



EC Current versus QL Scale Factor (E_dc Incl.)
EC Current (kA)
Dql Scale factor
0
50
100
150
200
0
1
2
3
4
5
□ Exptl. Conds.
96163, ρ/a = 0.17
Relatively small increase in IEC for ~ central CD.
96143, ρ/a = 0.37.
96152, ρ/a = 0.48
Doubling DQL increases IEC by 4x.

EC Current versus QL Scale Factor (No E_dc)



$\Rightarrow$ Strong increase in I_{EC} for $\rho_{CD} \sim 0.5a$ is reduced by absense of E_{DC}.

High Power, Finite Spot Size Considerations

- If the electron stays in resonance across the EC spot on a flux surface, the “kick” in velocity due to 2^{nd} harmonic resonance is $\approx v_{Te}$.
- Such kicks beyond range of validity of QL theory, may increase the stength of the wave-particle interaction, possibly leading to greater ECCD efficiency.
- (“Bucket” velocity space transport is obtained at even higher powers, *c.f.*, Nevins, Rognlien, B. Cohen, PRL, 1987).

Conclusions

- Observed high ECCD efficiency (above theory) cannot be due to inaccuracy in exptl. plasma profiles.
- (Incidentally, substantially higher theoretical off-axis efficiency is obtained at higher temperature).
- A factor of ~ 2 *ad hoc* increase in D_{QL} strength $\Longrightarrow$ theory and expt. in agreement.
- Higher power refinements of the D_{QL} calculation are being studied.