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PHYSICS ASSESSMENT OF NEUTRAL BEAM INJECTION IN CIT

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R. A. Dory

ORNL

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Livermore, CA

June 8-9, 1988

MASTER

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HEATING RELATED ISSUES FOR CIT

There are many important physics issues associated with auxiliary heating in CIT:

- Compatibility with H-Mode or other means of enhanced confinement
- Influence on impurity behavior
- Role in MHD beta limits
- Influence on sawtooth activity

The ability of CIT to address current drive is limited by its pulse length:

- Local perturbations to the plasma current occur on a skin time of $\tau_\eta = 1 - 10\,\mathrm{s}$
- Plasma current sources influence the total current and poloidal flux consumption on an L/R timescale of $\tau_{L/R} = 40 - 400\,\mathrm{s}$
- The skin time problem is overcome in inductive startup by growing plasmas and simultaneously ramping the toroidal field

ADVANTAGES OF NBI ON CIT

Physics of NBI heating has a large database:

- D-III-D, TFTR, JET as well as other experiments
- Beam attenuation and thermalization well understood
- Positive influence on H-Mode operation
- Plasma rotation with co-injection expels impurities
- Beam current drive (profile control) demonstrated
- Local kinetic and/or current perturbations suppress sawtooth instability as also observed with ICRH
- Small – but perhaps important – central fueling component
- Positive synergistic effects when combined with ICRH

Physics and technology relevant to ITER:

- High energy co-injection for current drive and impurity control in steady-state operation
- Multistep ionization processes may become important at high beam energies
- Heating profile insensitive to B and plasma edge conditions

CHOICE OF BEAM GEOMETRY AND ENERGY

Tangential co-injection preferred:

- Avoids fishbone activity and ripple losses associated with normal injection
- Expulsion of impurities
- Heating profile and shine-through less sensitive to plasma density because of double pass

Problems specific to tangential co-injection:

- More restricted access
- Higher energies required

Range and Shinethrough for Neutral Beam Trapping in CIT 2.1 — as Fcn of E_{beam} and n

- For tangency radius R_t = 1.7 m (rough optimum), the total beam path length in plasma is 4.4 m

- Including an estimate for the multi-step ionization process, the range in plasma is $1/n_e\sigma$:

Range in m

$n_{20}\backslash E_b$	0.5	1.0	1.5	2.0	Mev
1.0	1.4	2.4	3.3	4.2	
2.0	0.7	1.2	1.7	2.1	
3.0	0.5	0.8	1.1	1.4	
4.0	0.3	0.6	0.8	1.0	

$10^{20} m^{-3}$

- A more accurate integration of the beam trapping rate equation, using a standard density profile (α_n = 0.5) yields;

Shinethrough in %

$n_{20}\backslash E_b$	0.5	1.0	1.5	2.0	Mev
1.0	7	21	33	42	
2.0	0	4	11	17	
3.0	0	1	3	7	
4.0	0	0	1	3	

$10^{20} m^{-3}$

- Parameters assumed:
  R_o = 2.1 m, a_p = 0.65 m, A = 3.251, κ = 2, I = 11 MA
  B_o = 10T, [alt: I = 7.7 MA, B_o = 7 T]

NBI HEATING PROFILES

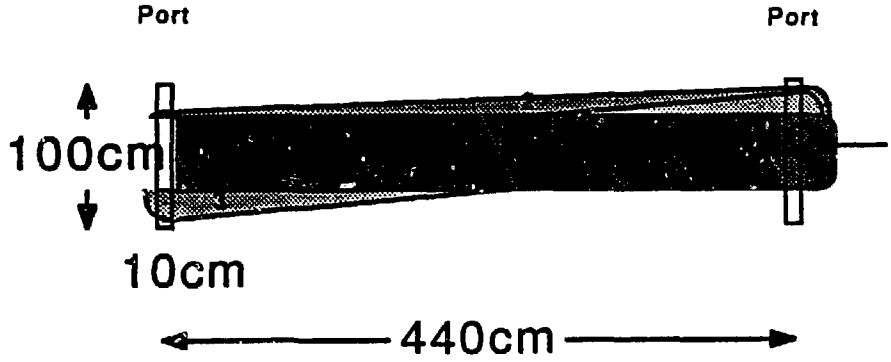
Assumptions for CIT ($R_o = 2.1\,\mathrm{m}$) heating examples:

- Tangency radius of 1.7 m
- Tangential access is limited to entrance and exit ports 0.1 m wide and 1.0 m high
- Uniform beam of rectangular cross-section 0.07 m wide and 0.4 m high
- Deuterium beams with $E_o = 1.5\,\mathrm{MeV}$
- Target plasma of $n_e(0) = 2 \times 10^{20}\,\mathrm{m}^{-3}$ and $T_e(0) = 10\,\mathrm{keV}$
- Unenhanced attenuation cross-sections

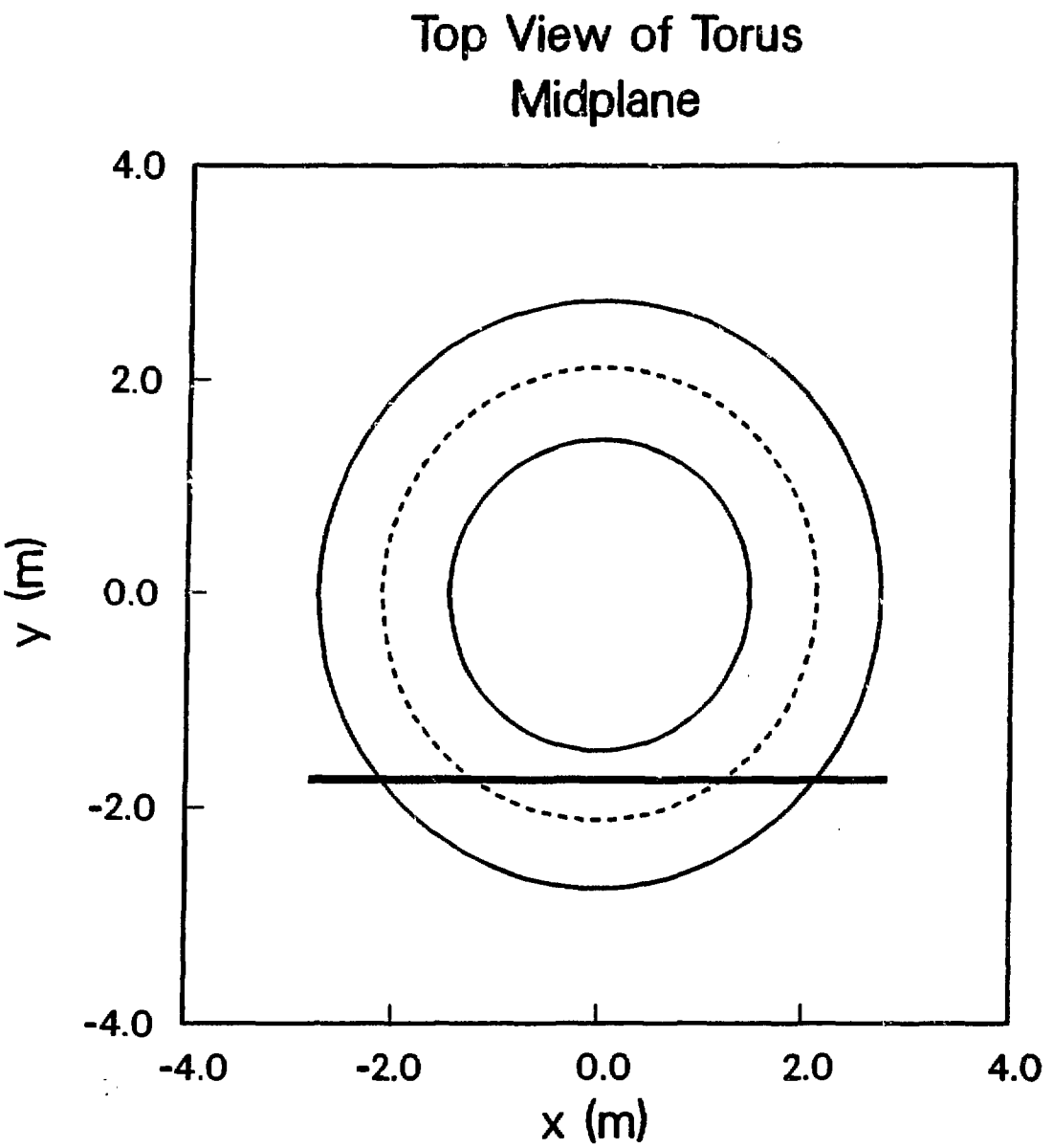
For a fixed heating profile and shine-through factor, beam energy and plasma density scale with the enhancement factor, G_σ, approximately as:

$$\frac{E_o}{n_e} \propto G_\sigma$$

Alternative Beam Trajectories



CIT High-Energy Beams



BEAM

Houlberg & Attenberger, ORNL

INPUT DATA

Plasma Geometry

Major Radius	: 2.100 m
Minor Radius	: 0.640 m
Elongation	: 2.00
Triangularity	: 0.40

Plasma Parameters

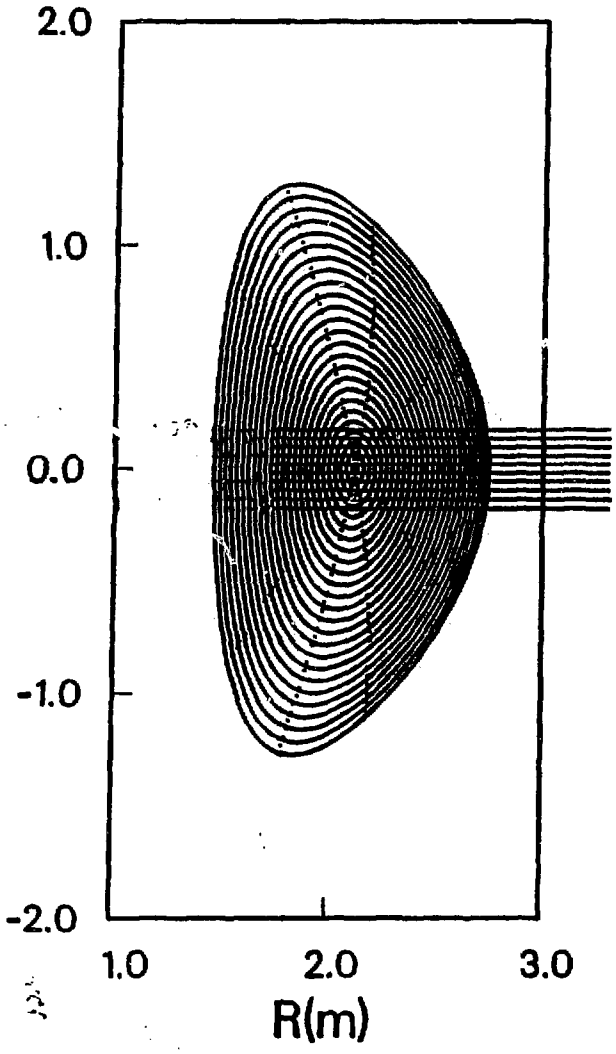
Toroidal Field	: 10.00 T
Plasma Current	: 11.00 MA
$T_e(0)$	: 10.00 keV
$n_e(0)$	: 2.00×10^{20} m^{-3}

Beam Parameters

Atomic Mass	: 2.0
Beam Energy	: 1500.0 keV
Tangency Radius	: 1.700 m
Beam Radius	: 0.04 m
Beam Power	: 10.00 MW

CIT High-Energy Beams

Plasma Cross-Section at Beam Entry



CASE 1
Horizontal

BEAM

Houlberg & Attenberger, ORNL

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CIT High-Energy Beams

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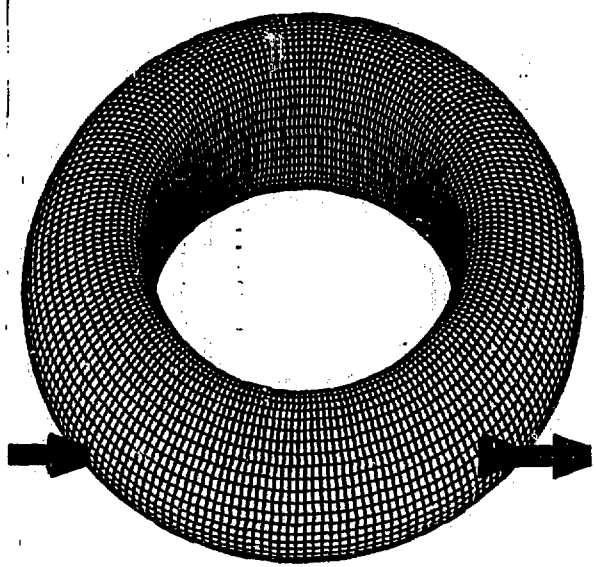

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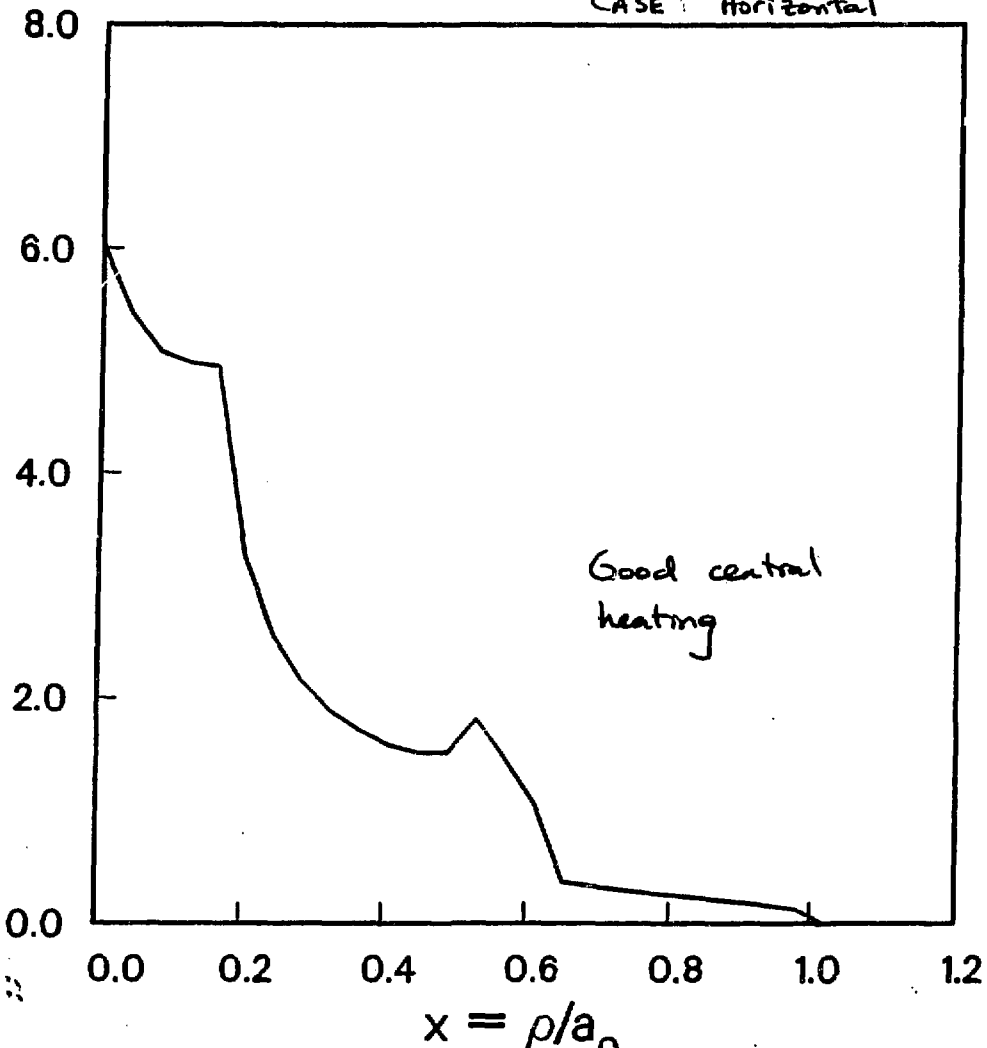
CIT High-Energy Beams

Normalized Fast Ion Source H(x)

CASE: Horizontal



BEAM

Houlberg & Attenberger, ORNL

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CIT High-Energy Beams

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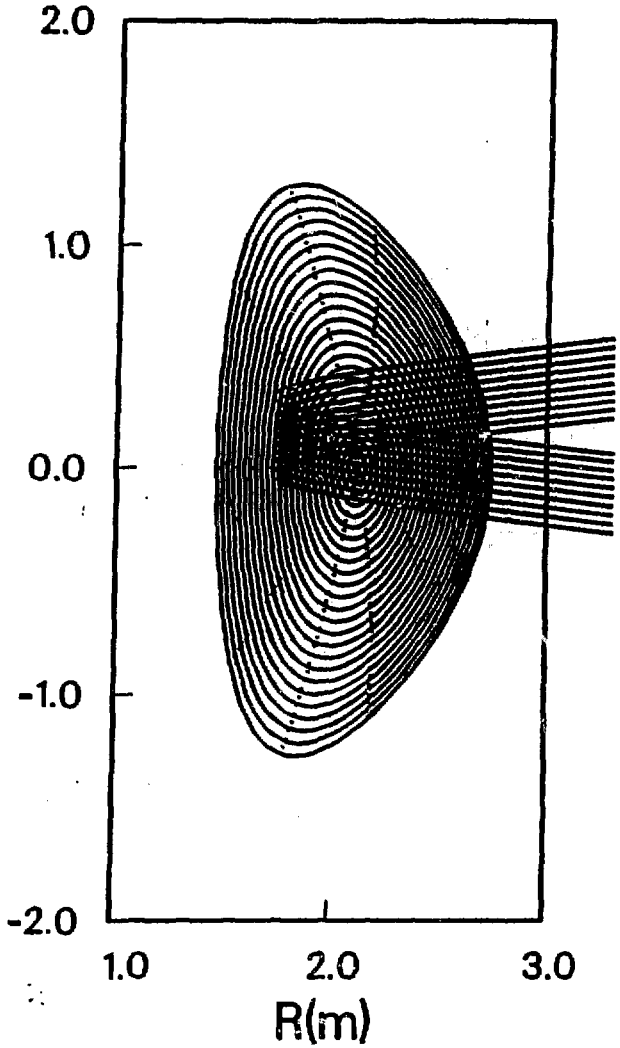

CASE 2
Tilted & raised

BEAM

Houlberg & Attenberger, ORNL

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Elongation	: 2.00
Triangularity	: 0.40

Plasma Parameters

Toroidal Field	: 10.00 T
Plasma Current	: 11.00 MA
$T_e(0)$	: 10.00 keV
$n_e(0)$	: 2.00×10^{19} m^{-3}

Beam Parameters

Atomic Mass	: 2.0
Beam Energy	: 1500.0 keV
Tangency Radius	: 1.700 m
Beam Radius	: 0.04 m
Beam Power	: 10.00 MW

CIT High-Energy Beams

CASE 2
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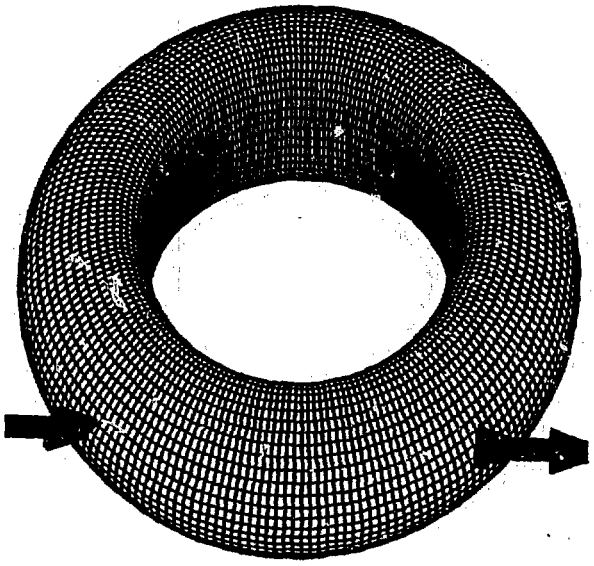

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Houlberg & Attenberger, ORNL

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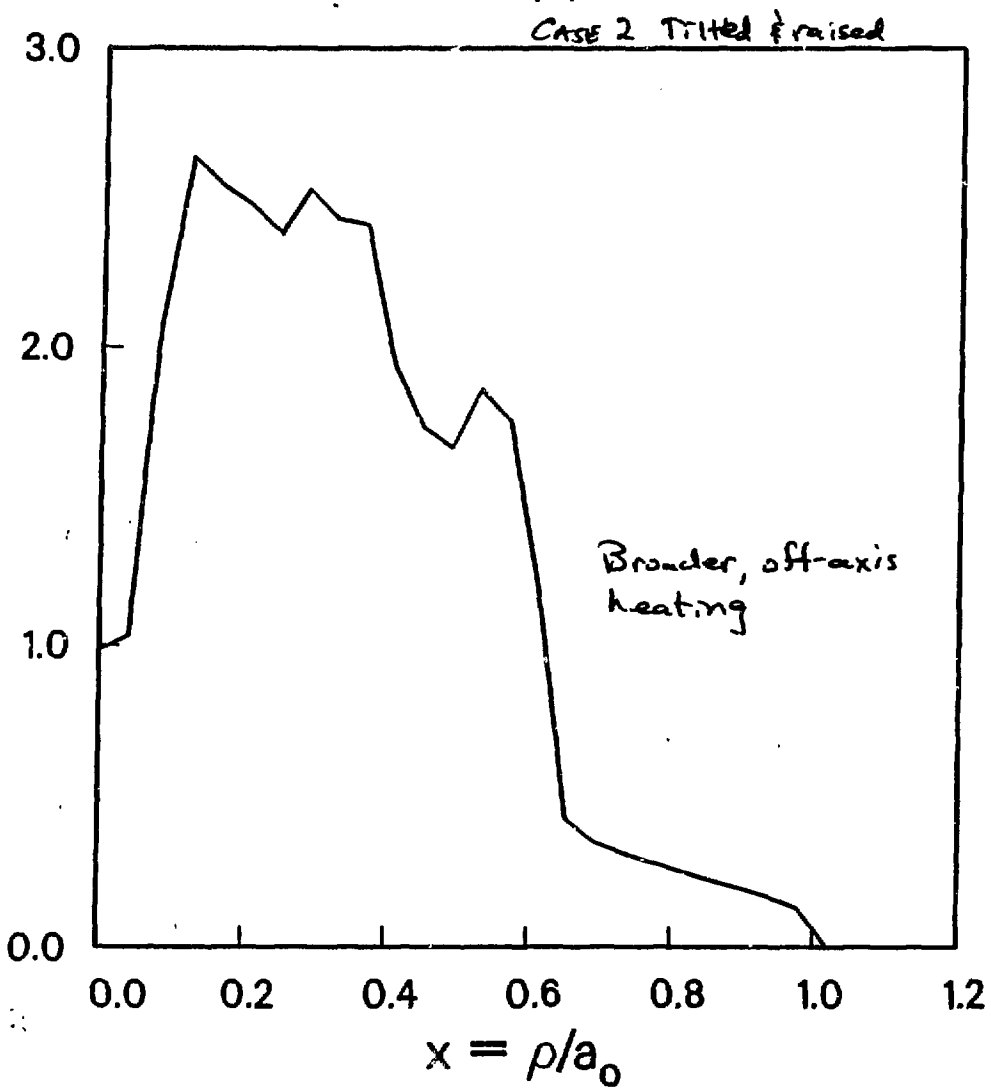
CIT High-Energy Beams

Normalized Fast Ion Source H(x)



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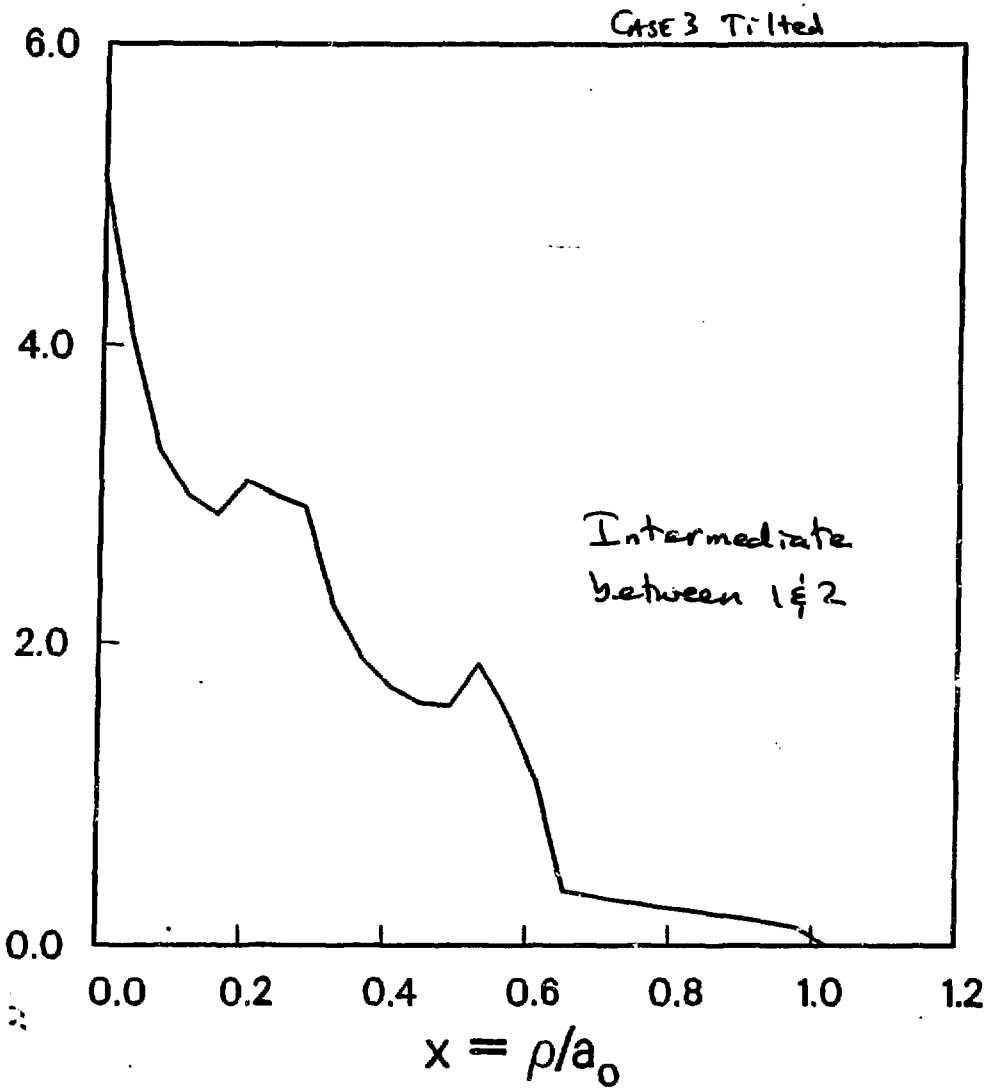
CIT High-Energy Beams

Normalized Fast Ion Source H(x)



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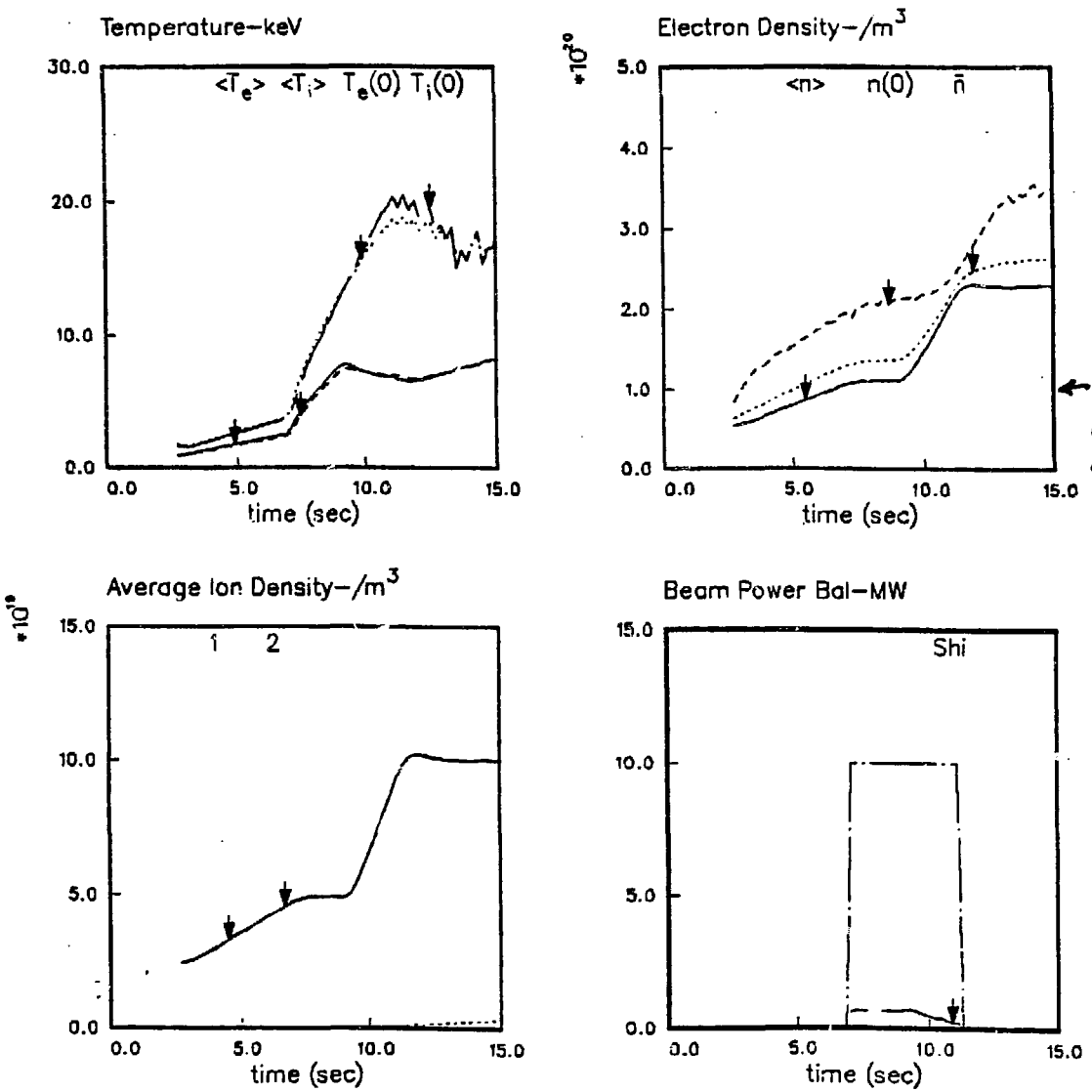
WHIST Simulation of CIT Beam Injection

1 Mev Deuterium Injection



← Density held low during initial heating

WHIST Simulation of CIT Beam Injection

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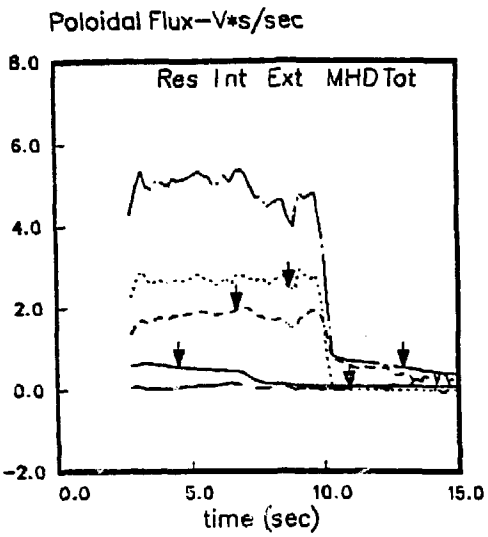
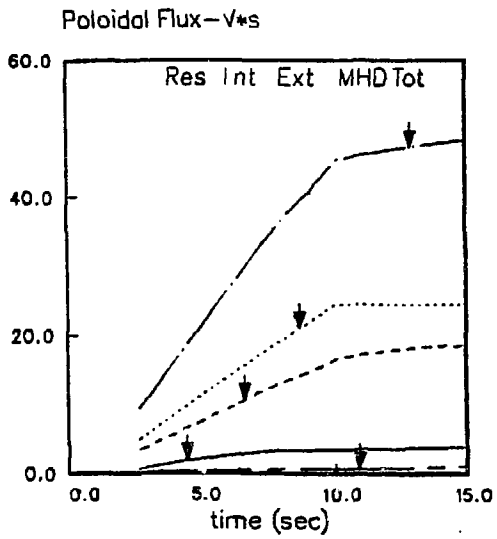
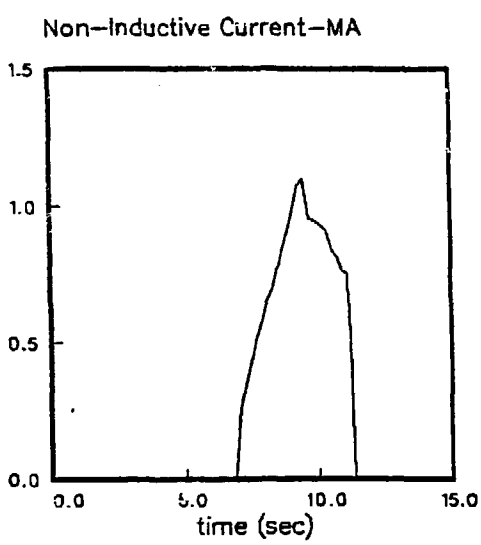
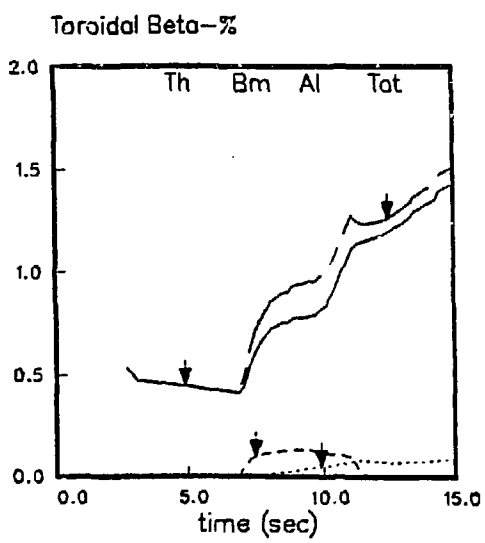








Net effect on V-s from beam current ~ 0.03 V-s

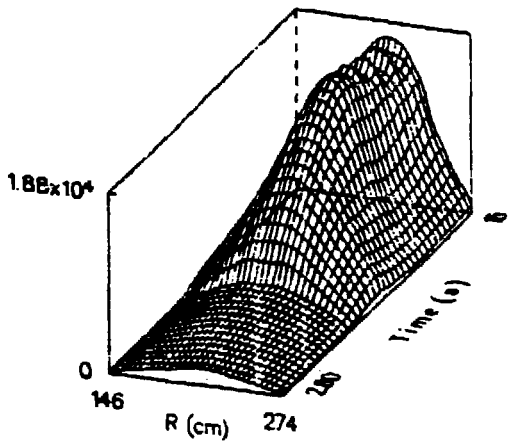
$I_s \simeq 1$ MA, $R_\Omega \approx .01\,\mu\Omega$, $\Delta t_{CD} \simeq 3$ s

$$\Psi_{CD} = \int I_s R_\Omega \, dt \simeq 0.03 \text{ V-s}$$

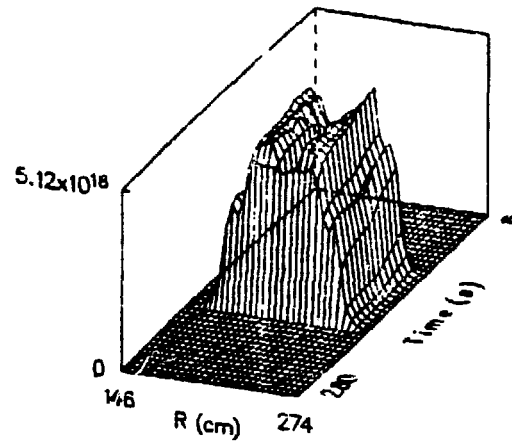
WHIST Simulation of CIT Beam Injection

1 Mev Deuterium Injection

electron temp. (ev)

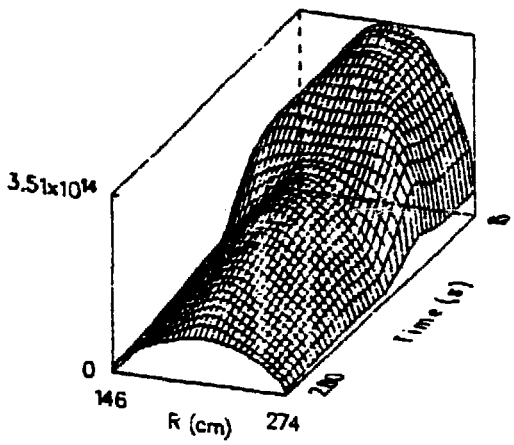


aux. pwr (ev/s/cm3)

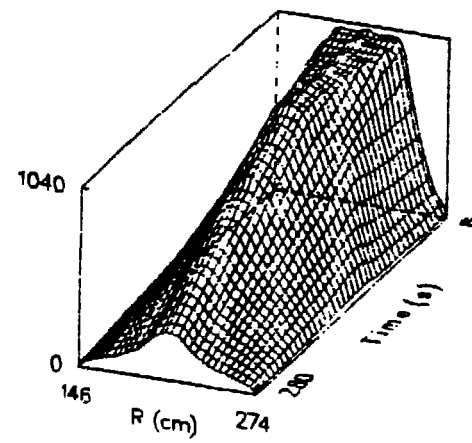


Beam heating profile fairly constant

electron dens(/cm3)



current density



Plasma Rotation Estimate

$$dP_{beam}/dt = dP_{plasma}/dt$$
$$(I_b/e)\, m_b\, v_b = n_i\, m_i\, V_p\, dv/dt$$

Momentum Injection by Tangential Neutral Beam Injection
Nominal beam and plasma parameters for CIT

Ib	1.0E+01	Amp	ni	1.0E+20	/m³
Eb	1.0E+06	eV	Ti	1.0E+04	
AMUb	2		AMUi	2.5E+00	
Zb	1				
mb	3.34E-28	kg	mi	4.2E-28	
vb	9.8E+06	m/s	vi	6.9E+05	m/s
Pb	10	MW			

Momentum confinement time from TFTR data
Scaled from Stacey & Sigmar theory

TFTR			CIT		
RoTFTR	2.58	m	RoCIT	2.1	m
ATFTR	3.15		ACIT	3.251	
κTFTR	1		κCIT	2	
BTFTR	4.7	T	BCIT	10	T
TiTFTR	2.0E+03	eV	TiCIT	7.0E+03	eV
VOLplas	34	m³	VOLplas	35	m³
Zeff	2		Zeff	1.1	
** RoB²Zeff/Ti			** Ro²BZeff/Ti		
* tauΦTFTR	0.100	s	tauΦCIT	0.022	s
(Ib/e)vb/(niVp)*(mb/mi)			(Ib/e)vb/(niVp)*(mb/mi)		
accel	5.7E+05	m/s²	accel	1.4E+05	m/s²
* vrot	1.2E+05	m/s	vrot	7.5E+03	m/s

momentum confinement

rotation velocity

* ref: S. Scott EPS 87, Vol I, p 65.
** ref: Stacey & Sigmar, PF 28 (1985), p 2800.

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Study in CIT of Alfvén Stability with High Energy Beams — an ITER Issue

- Unstable coupling of beam ions to Alfvén waves (shear and compressional) is an issue for current drive with beams. In ITER, high energy ($\gtrsim$ 1.7 MeV) is needed for penetration if the device grows beyond R_o = 4-5 m

- Since the coupling can be varied by changing parameters, CIT could assess importance of: rates of anomalous slowing down, spatial ion diffusion, and coupling to alpha particles. With typical parameters for current drive experiments in CIT:

  > $v_{D \text{ or } H} \approx 1.2 \cdot 10^7$ m/s at 1.5 MeV/amu .
  > $v_{Alfvén} \approx 1.4 \cdot 10^7$ m/s at 10^{20} m^{-3}, and 10 T, assuming μ_{plasma} =2.5 (50% D, 50% T)

- Conclusion: For typical current drive operation the beam is subAlfvénic and no unstable coupling occurs

- How can one change operation to study instability?

  > Reduce B: Operate at 8.5 T
  > Raise n_e: Operate at $2 \cdot 10^{20}$ m^{-3}. Increases slowing down process
  > Raise beam energy. Would require 2 MeV/amu

- After the velocity criterion for instability is satisfied, CIT could determine the consequences as function of other stability parameters, n_b/n_e, T_e, ...

SUMMARY

The large existing NBI database and our understanding of beam physics indicates that high energy neutral beams could be a very attractive back-up option for CIT:

- Flexibility of the heating profile is possible even with very restricted access
- Co-injection may provide an extra benefit in impurity control
- Access to enhanced confinement regimes, e.g., H-Mode

High energy beam technology development should be pursued so that CIT could take advantage of these beneficial aspects of NBI