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Multi-Pulse DARHT Machine-Plasma Plume Problem

Eugene J. Lauer

Abstract

The plasma current decay time constant is predicted to be short compared to the pulse length and so self-focusing is predicted for most of the beam pulse. Four- pulse beam envelopes for a high dose case require mitigation, those for a low dose case do not. Methods of mitigation are summarized. Hose instability growth in the plume length is predicted to be minimal.

I-Introduction

The four- pulse DARHT machine is predicted to cause plasma plumes to expand upstream from the target. If the electron beam is self-focused in a plume, the focal spot moves upstream from the original position. This problem was first analyzed by Oliver in 1999 (1). He concluded that the beam would become self-focused in a time short compared to the pulse length, and suggested that the problem could be corrected by adjusting the strength of the final focusing lenses between pulses.

Subsequently extensive calculations have become available of the plume mass density, electron density and electron temperature. In Sect. II we calculate the time for self-focusing to develop, Sect. III shows some examples of beam envelopes with different plume lengths, Sect. IV presents methods of mitigating the problem and Sect. V calculates hose instability transverse oscillation amplitude growth in the plume length.

A related problem is beam defocusing due to positive ions accelerated upstream from the target by the self E_z field during a single pulse. Ion barriers are being tested at the Livermore ETA II accelerator.

II-Calculations of the plasma current decay time constant

For the exponential decay time constant of the axially symmetric plasma current we use the magnetic diffusion time constant (2)

$$\tau_m = \frac{4\pi\sigma a^2}{c^2} \qquad \text{(Gaussian units)} \qquad 1$$

where σ is the conductivity and a is the beam radius and c is the velocity of light. (Note that Oliver used 2π).

$$\sigma = \frac{e^2 n_e}{m\nu_m} \qquad 2$$

where e and m are the charge and mass of the electron, n_e is the electron density and ν_m is the collision frequency for momentum transfer. Combining Eqs. 1 and 2,

$$\tau_m = \frac{4\pi e^2 n_e a^2}{c^2 m v_m} \qquad 3$$

We have used Darwin Ho's calculations of target expansion using the LASNEX program. Numerical calculations of τ_m were made for a "high dose" case with pulse times, pulse lengths and plume upstream edges shown in Table I.

Table I-High Dose Parameters

PULSE	PULSE TIME	PULSE LENGTH	PLUME EDGE Z
	(μs)	(ns)	(cm)
1	0	75	2.7
2	0.6	75	2.1
3	1.2	75	1.4
4	1.86	110	0.9

The target consisted of four thin Ta foils equally spaced in a length of 1.1 cm. The r.m.s. beam radius was .067 cm. The original (pulse 1) position of the upstream edge of the target was 2.7 cm. τ_m was calculated for conditions at the start of pulse 4, on axis, every 0.5 cm of z.

For the electron density we use the sum of the thermal density n_{et} calculated by Darwin Ho using the Saha equation and the density produced by beam electron collisions, n_{eb}.

$$n_e = n_{et} + n_{eb} \qquad 4$$

n_{eb} is calculated using

$$\frac{dn_{eb}}{dt} = \frac{I_b \sigma_b n_g}{e_p \pi a^2} - \alpha n^2{}_{eb} \qquad 5$$

where I_b is the beam current (2000A), $\sigma_b = 2.3x10^{-18}\ cm^2$,(Ta at 18 Mev), $e_p = 1.6x10^{-19}$ coul. , n_g is the Ta gas atom density and α is the recombination coefficient. The recombination coefficient is not known for Ta. In gases that form molecular ions, eg $N_2^+, O_2^+, He_2^+, Ar_2^+, Kr_2^+, Xe_2^+, Hg_2^+, Cs_2^+$ there is strong recombination. The energy released in recombination is dissipated by dissociating the molecule ("dissociative recombination"), with $\alpha \sim 10^{-7} cm^3 \sec^{-1}$. Gases with atomic ions have a much smaller α because the energy of recombination must be dissipated by radiating a photon. We calculate τ_m for two extreme values of α :$10^{-7} cm^3 \sec^{-1}$ and 0. For $\alpha = 0$ we integrate Eq 5 over the time of the first three pulses (3x75ns). The characteristic time to reach the recombination-limited density is $1/n_e\alpha$ which is 1 ns for $n_e = 10^{16} cm^{-3}$ and $\alpha = 10^{-7} cm^3 \sec^{-1}$. Fig 1 presents n_g and Fig 2 presents n_e from the different sources.

For ν_m we use the sum of the rate for electron-ion collisions (Spitzer rate) and that for electron-gas molecule collisions

$$\nu_{ei} = \frac{4\sqrt{2\pi}e^4 \ln \lambda n_e}{2.03x10^{-18} 3\sqrt{m}(T\,(ev))^{3/2}}$$

$$\nu_{ei} = 2.90x10^{-6} \frac{\ln \lambda n_e}{T(ev)^{3/2}} \qquad 6$$

where λ is the ratio of maximum to minimum impact parameters in coulomb scattering.

$$\lambda = \frac{3(kT)^{3/2}}{2e^3\sqrt{\pi n_e}} \qquad 7$$

(Note that the above rate is given in all the later books e.g. (2). The rate in Spitzer's book is about 1/3 as large).
We use a typical gas collision rate

$$\nu_{eg} = 1.5x10^{-7} n_g \qquad 8$$

Fig 3 shows T_e and Fig 4 shows ν.

Fig 5 presents τ_m vs z. using a[z] of pulse 1 on Fig 7. Three curves are shown: $\alpha = 0$ and $\alpha = 10^{-7} cm^3 \sec^{-1}$ discussed above and that for Spitzer conductivity with ne=net. For Spitzer conductivity we combine Eqs. 3 and 6 (neglecting electron collisions with neutral molecules) giving

$$\tau_m = \frac{4\pi e^2 T(ev)^{3/2} a^2}{c^2 m 2.90x10^{-6} \ln \lambda} = 1.21x10^{-6} \frac{T(ev)^{3/2} a^2}{\ln \lambda} \qquad 9$$

In this case, τ_m is only weakly dependent on n_e through $\ln \lambda$, and is mainly determined by the temperature and the conducting channel radius.

Fig 6 shows τ_m calculated using Spitzer conductivity and a=.0351 cm, (the equilibrium radius) everywhere.

These calculations were all done for the conditions at the start of pulse 4. At the start of pulses 2 and 3 the electron temperature is lower and so τ_m would be shorter.

Self-focusing also requires that the self-E_r be neutralized. At a gas density of $10^{16} cm^{-3}$, beam ionization neutralizes the beam in about 1.5 ns.

The important conclusion from these calculations is that the plasma current decay time constant is short compared to the pulse length and so we predict self-focusing. This can cause the beam envelope to be different for different pulses as shown in the next section.

The ideal τ_m is either long compared to the pulse length so that there is no self-focusing, or short compared to the pulse length so that there is self-focusing but at least the focusing is constant during most of the pulse. We predict a maximum τ_m of 3-6 ns which is fairly short compared to the shortest pulses(26 ns).

III-Examples of self-focused beam envelopes with different plume lengths

We use an rms beam envelope equation with an emittance term and a self-force term with full self B_ϑ

$$\frac{d^2a}{dz^2} = \frac{\varepsilon^2}{a^3} - \frac{(f - 1/\gamma^2)I(kA)}{(1 - 1/\gamma^2)17.05\beta\gamma a} \qquad 10$$

DARHT parameters are I=2kA, kinetic energy=18 Mev, emittance, $\varepsilon = 2x10^{-3}$ rad. cm. f is the fractional neutralization of E_r .In vacuum f=0, in a plume f=1. β is v_z / c and γ is the beam electron total energy in rest mass units.. Note that we have modeled ε as constant, actually it would increase with z due to scattering.

Figs7 and 8 are for the high-dose parameters of Table I. Fig 7 has pulse 1 injected with a[2.7cm] = .05 cm, a'[2.7]=0. The other pulses make the transition to self-focusing at the positions shown in Table I. Fig 8 is similar to Fig 7 except that pulse 1 has the equilibrium radius (.0351 cm) for Z>2.7 cm. The later pulses are quite defocused and mitigation is required for the high-dose case.

Figs 9 and 10 are for a "low-dose" set of parameters shown in Table II.

Table II-Low Dose Parameters

PULSE	PULSE TIME	PULSE LENGTH	PLUME EDGE Z
	(μs)	(ns)	(cm)
1	0	26	2.5
2	0.6	26	2.4
3	1.2	44	2.2
4	1.8	110	1.6

The temperatures for the low-dose case are lower than for the high-dose case and so τ_m would be shorter and self-focusing is predicted. Fig 9 has pulse 1 injected with a[2.5]=.05 cm, a'[2.5]=0. The other pulses make the transition to self-focusing at the positions shown in Table II. Fig 10 is similar to Fig 9 except that pulse 1 has the equilibrium radius (.0351 cm) for a$\geq$2.5 cm. The beam envelopes for Fig 9 are acceptable and mitigation is not required for the low-dose case.

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IV- Methods of mitigating the beam envelope-plume problem

Fig 11 depicts the use of two fast lenses programmed to match the beam envelope to the equilibrium radius (.0351 cm) for each of the plume transition points, (points where the envelope changes from vacuum to self-focusing.)

Another class of schemes involves providing a resistive plasma in a region as long as the longest plume, (see Fig 12). The beam envelope would be matched to the desired a and a' at the upstream edge of the resistive plasma and the envelope would be the same regardless of the plumes. There are two sub-cases:

1-The gas is ionized by the beam and the gas density is high enough so that the transition to self-focusing occurs in a ns or less.(There must not be a low density halo which would result in a neutralization time comparable with the pulse length.) Examples are:

a-Dick Briggs' proposal in which the gas is held in a cell with an upstream foil. The beam envelope is large at the foil so that the foil will survive and executes a half oscillation and has a small radius at the target.

b-The gas jet that is being tested at ETA II.

2-Low density gas (about equal to the beam density) is ionized by some auxiliary means, e.g. a laser or microwaves (3).

V-Hose Instability

In the problems discussed above, the beam envelope is axi-symmetric. For the hose instability, the center of mass of the beam oscillates transversely in the self-B field. The oscillation amplitude grows exponentially with z from small time dependent perturbations at z=0. Fig 13 shows the theoretical growth rate, Ω_i for sinusoidal time dependence at z=0. Maximum growth rate with z occurs at $\varpi\tau_d \approx 0.5$, where τ_d is the dipole plasma current decay time constant, (about 1/8 the time constant for the axially symmetric mode discussed above, i.e. about 1ns.) In this case the frequency for maximum growth rate is about 10^8 cps. The maximum growth rate is about $0.2k_\beta$, i.e. about 0.46 cm^{-1}. For 3 cm length, the growth factor is about 4. The predicted maximum growth is so small that hose instability is probably not a problem.

References

1-Bryan V. Oliver, Dale R. Welch and Thomas P. Hughes, Beam-Target Interactions in Single and Multi-Pulse Radiography, MRC/ABO-R-1909,1999

2-Krall and Trivelpiece, Principles of Plasma Physics, McGraw-Hill,1973

3-E. J. Lauer, Modeling the Use of Self-Focused Beams to Overcome the Effects of Target Emissions in Advanced Hydrodynamic Radiography Machines, UCRL-ID-143423,May1,2001

Acknowledgments:

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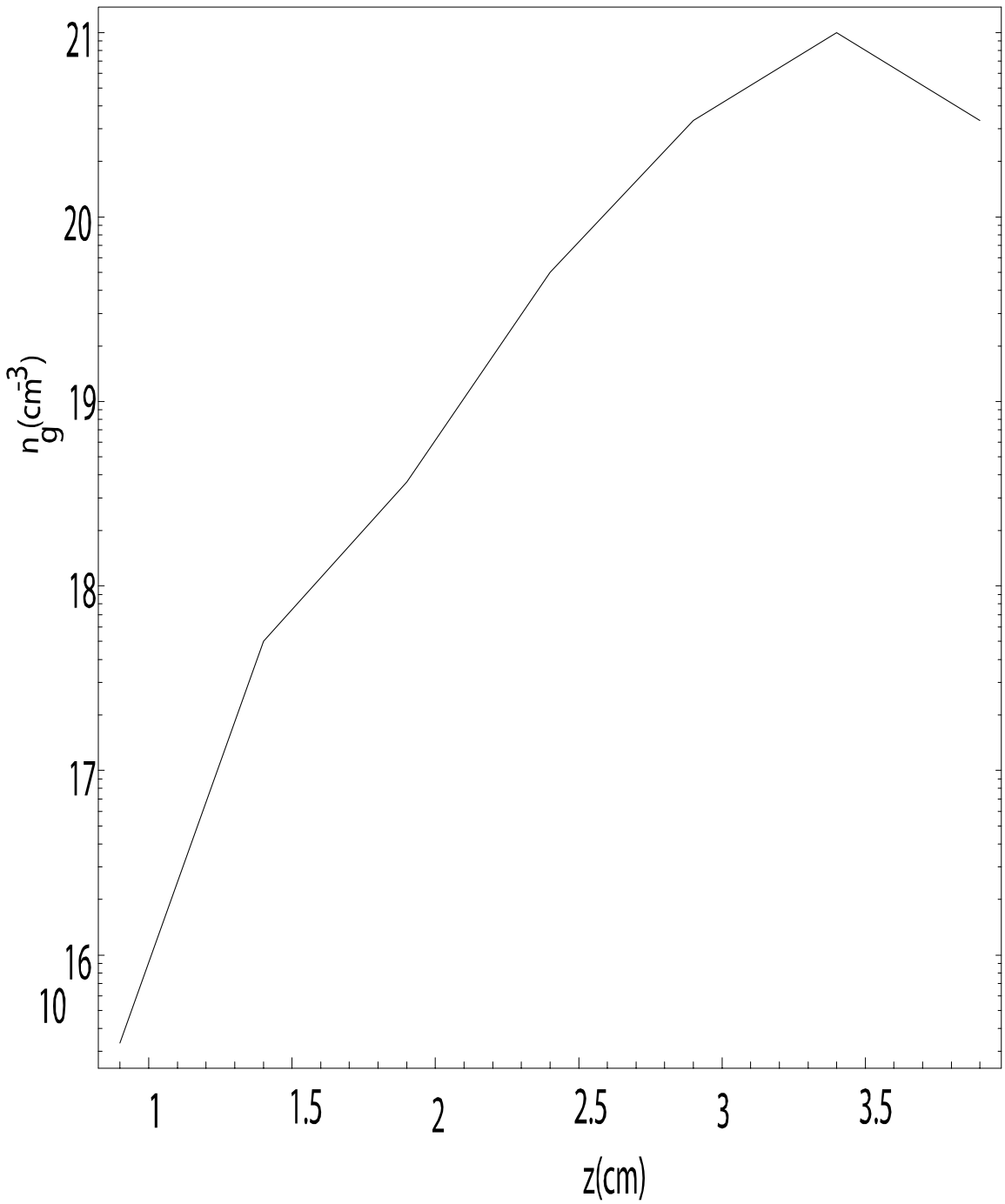

Fig1-ng vs z, start of pulse 4

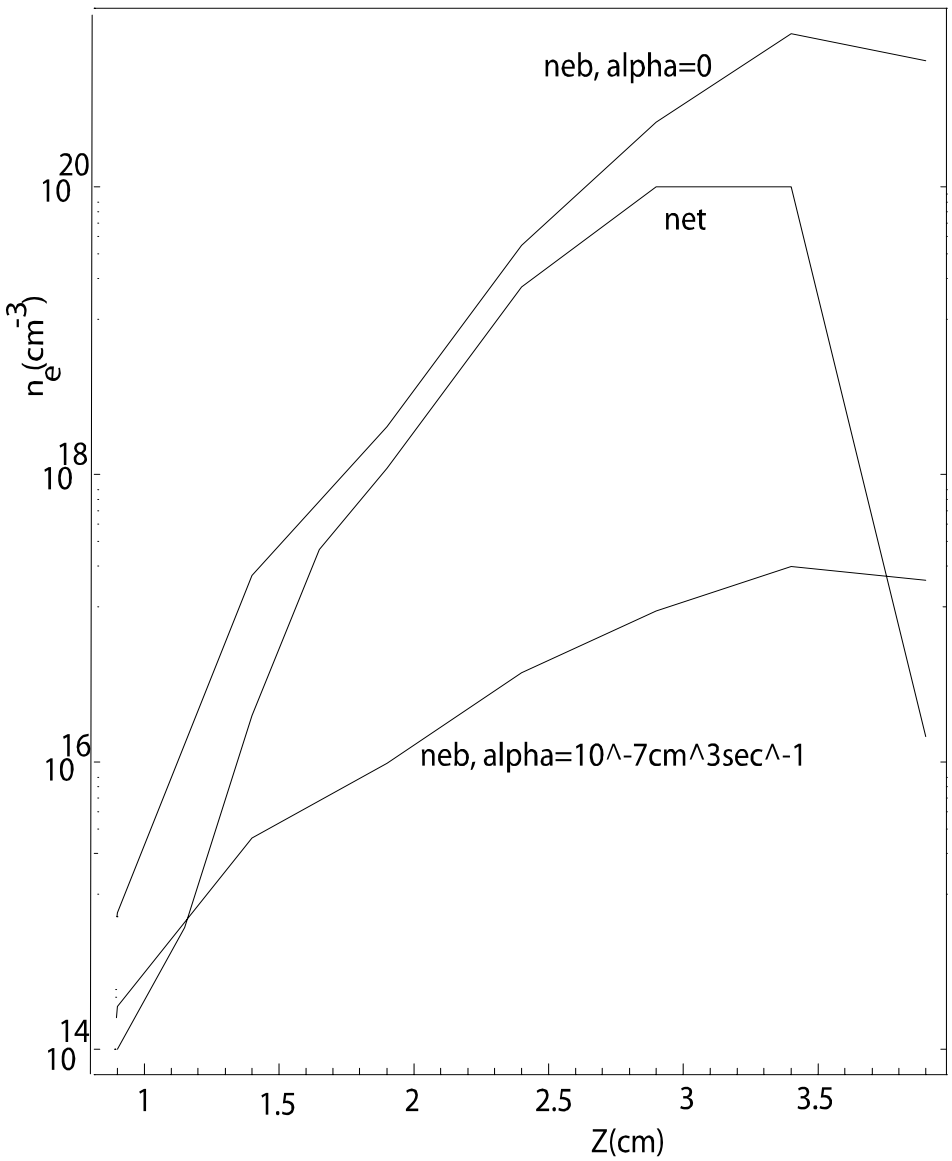

Fig2- ne vs Z, start of pulse 4

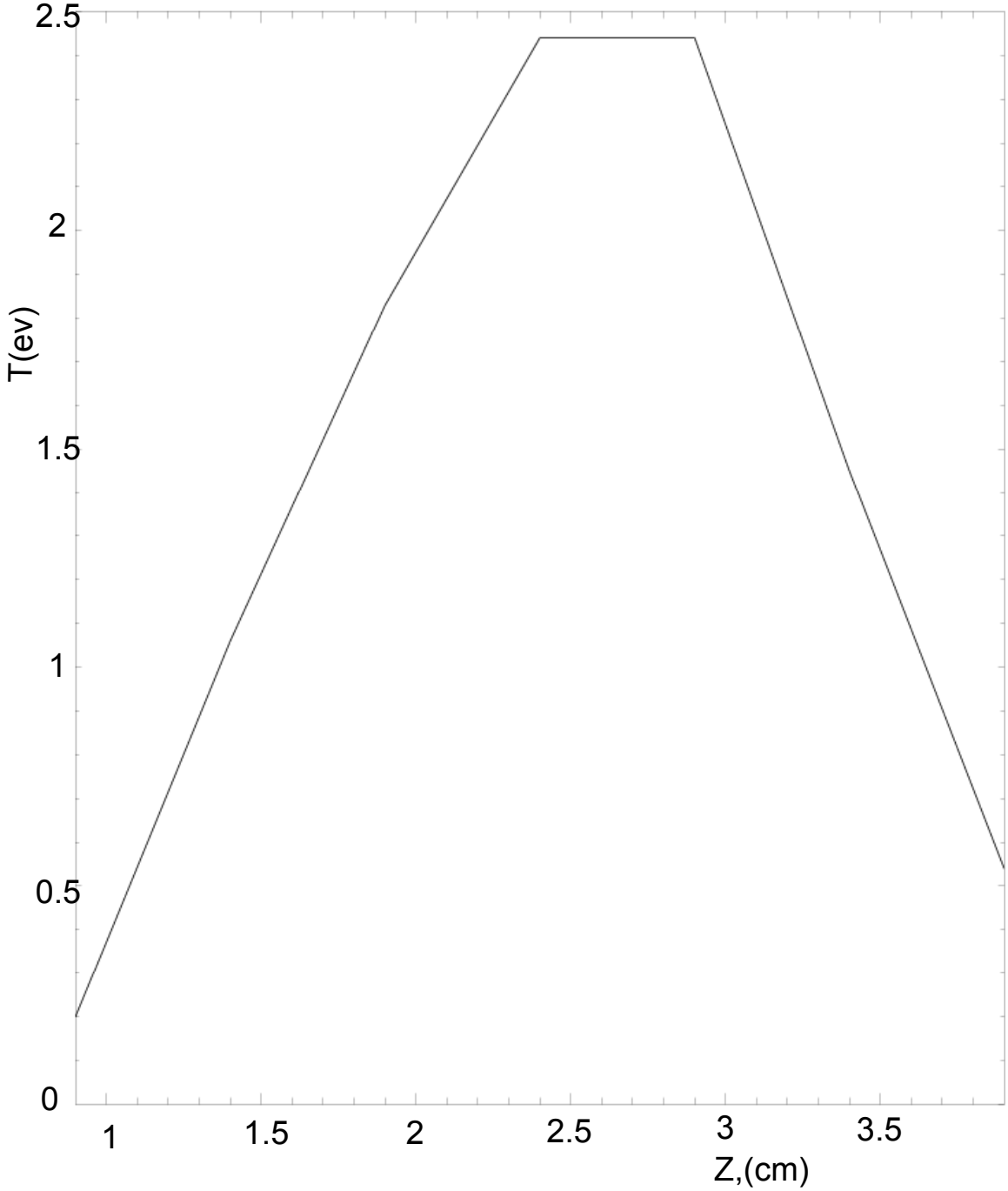

Fig3-T_e vs Z,start of pulse 4

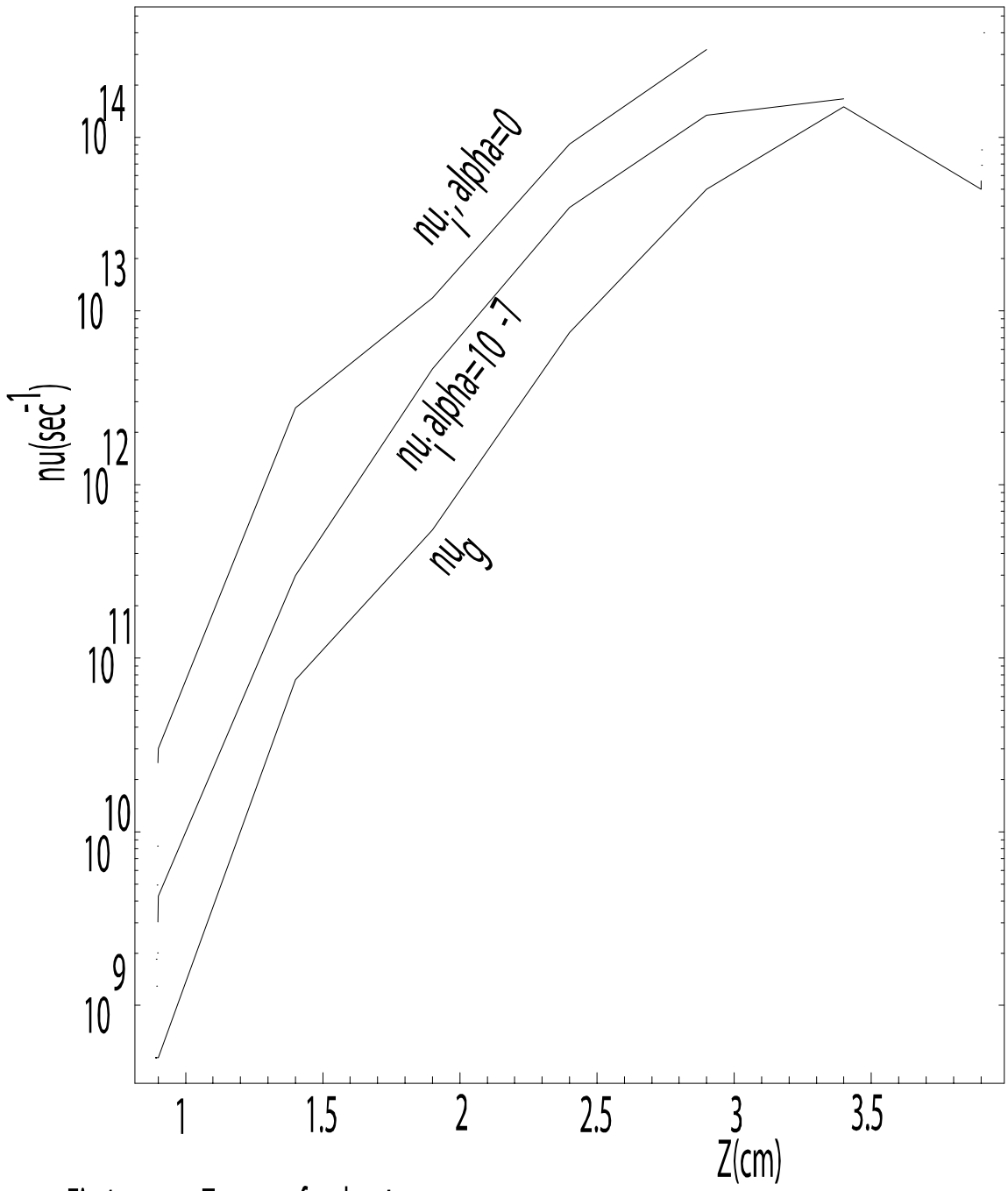

Fig4-nu_m vs Z, start of pulse 4

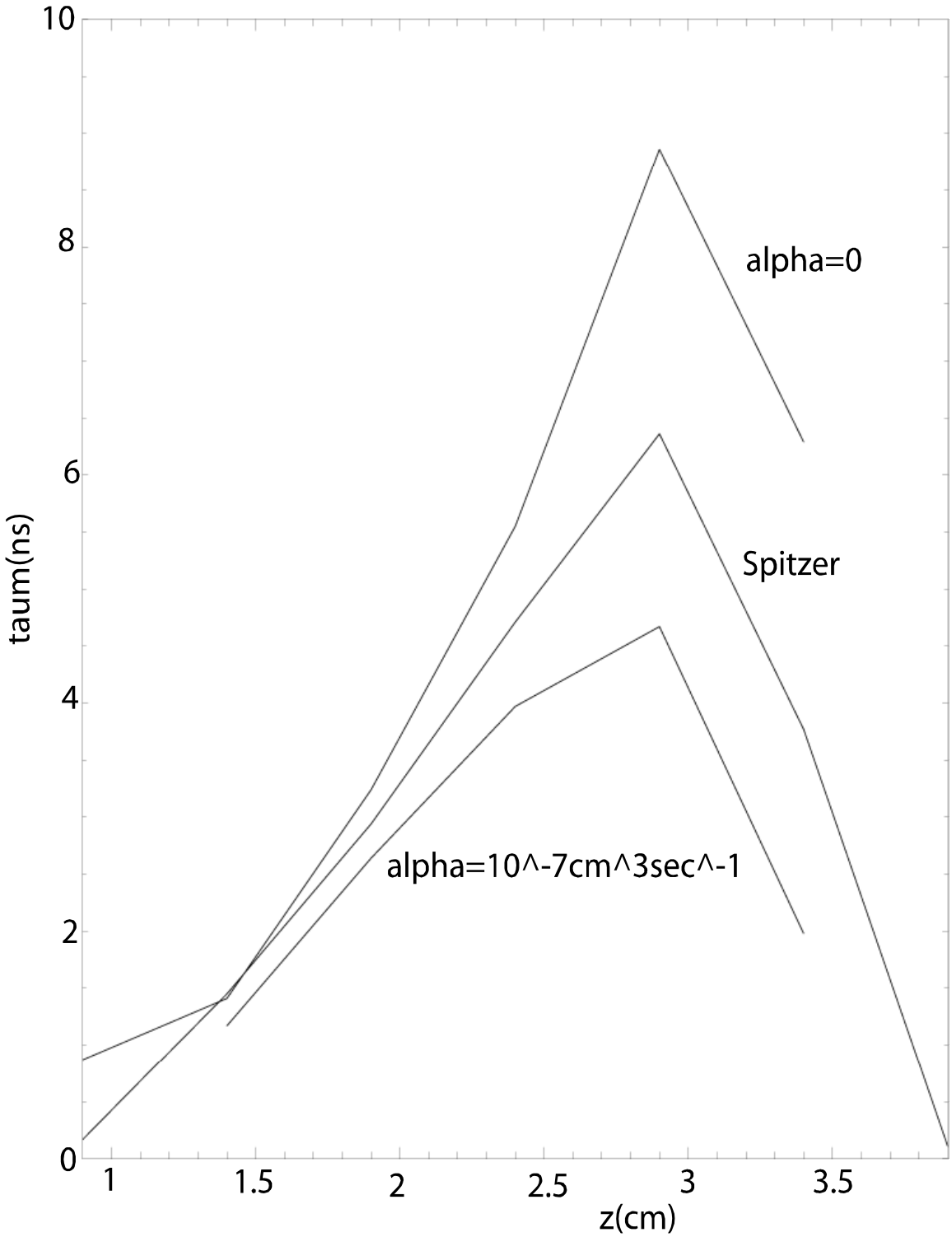

Fig5-taum vs z with a[z] of Fig7, pulse 1

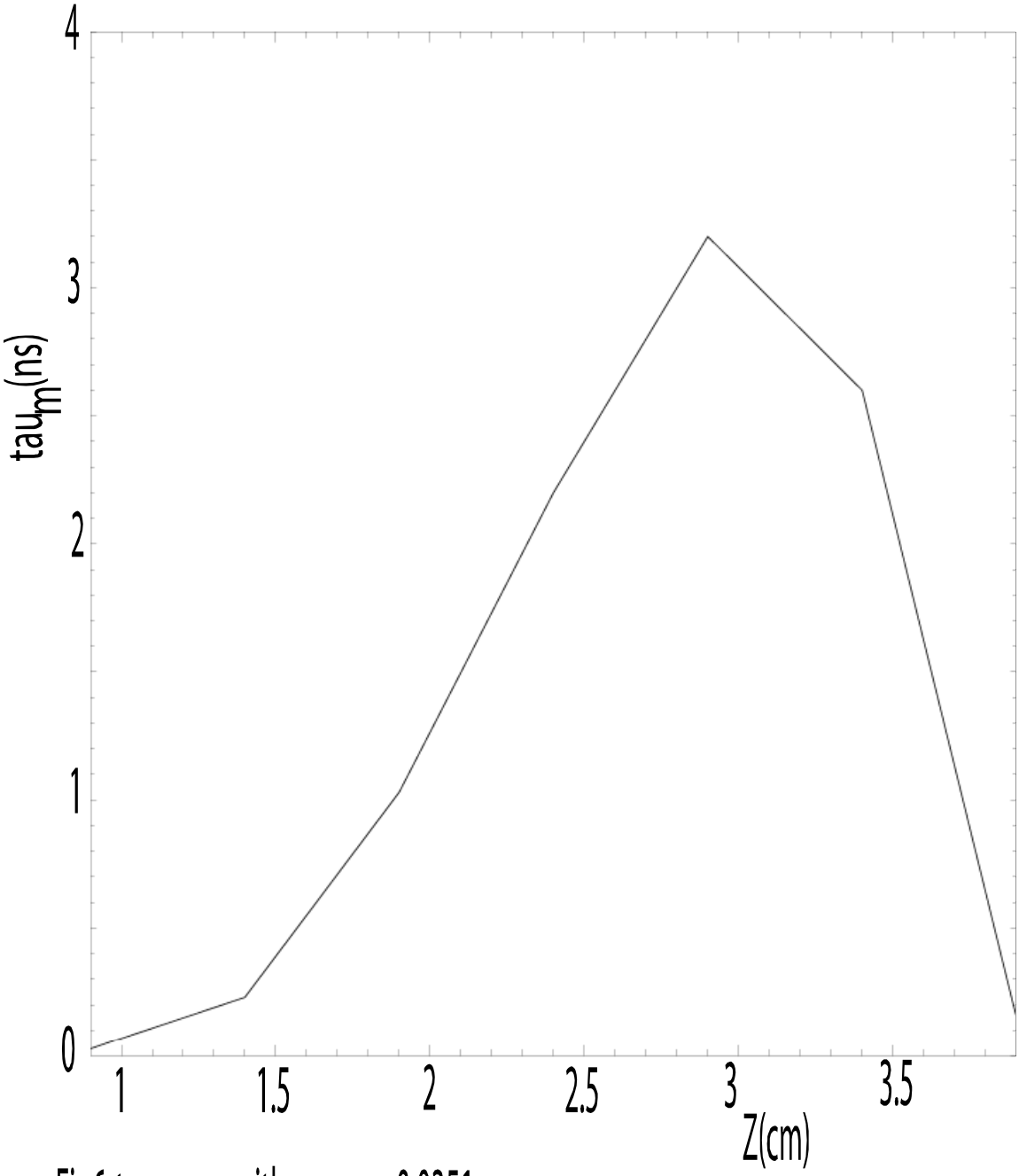

Fig6-tau_m vs z with a= a_{eq} =0.0351 cm

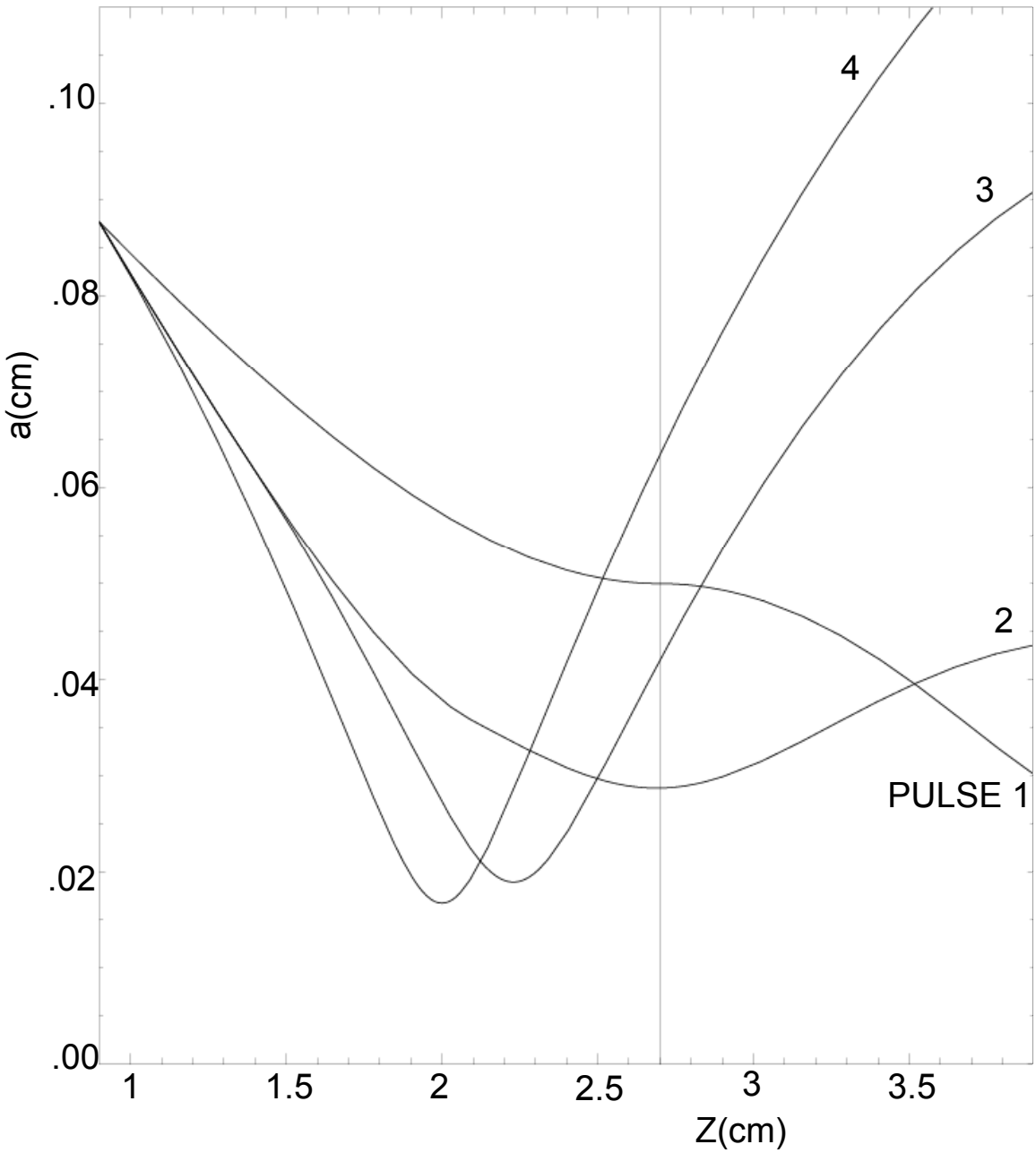

Fig 7-a vs z for four DARHT pulses with pulse 1 injected with a[2.7]=0.05 cm, a'[2.7]=0, high dose

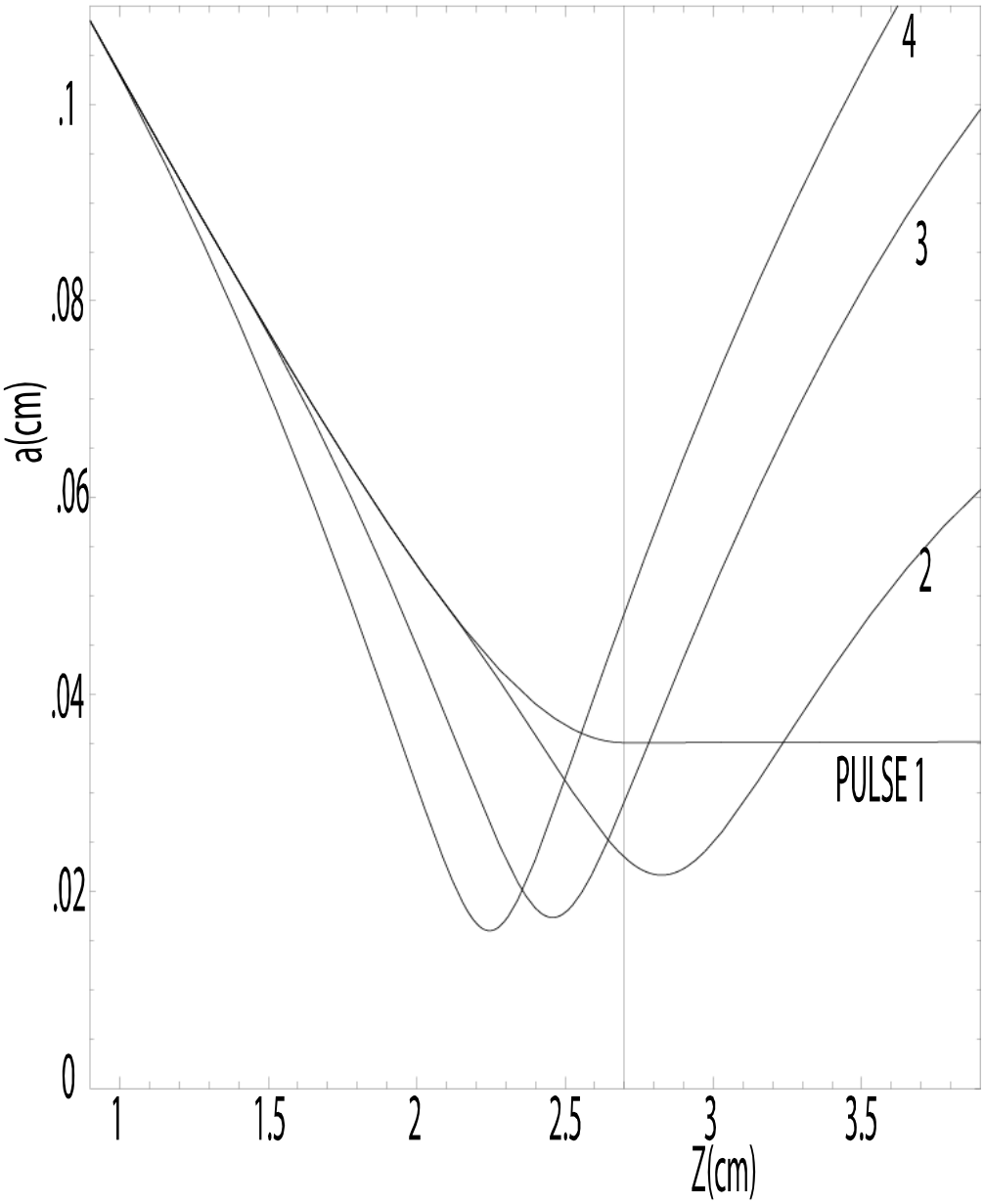

Fig 8- a vs z for four DARHT pulses with pulse 1 injected in equilibrium, high dose

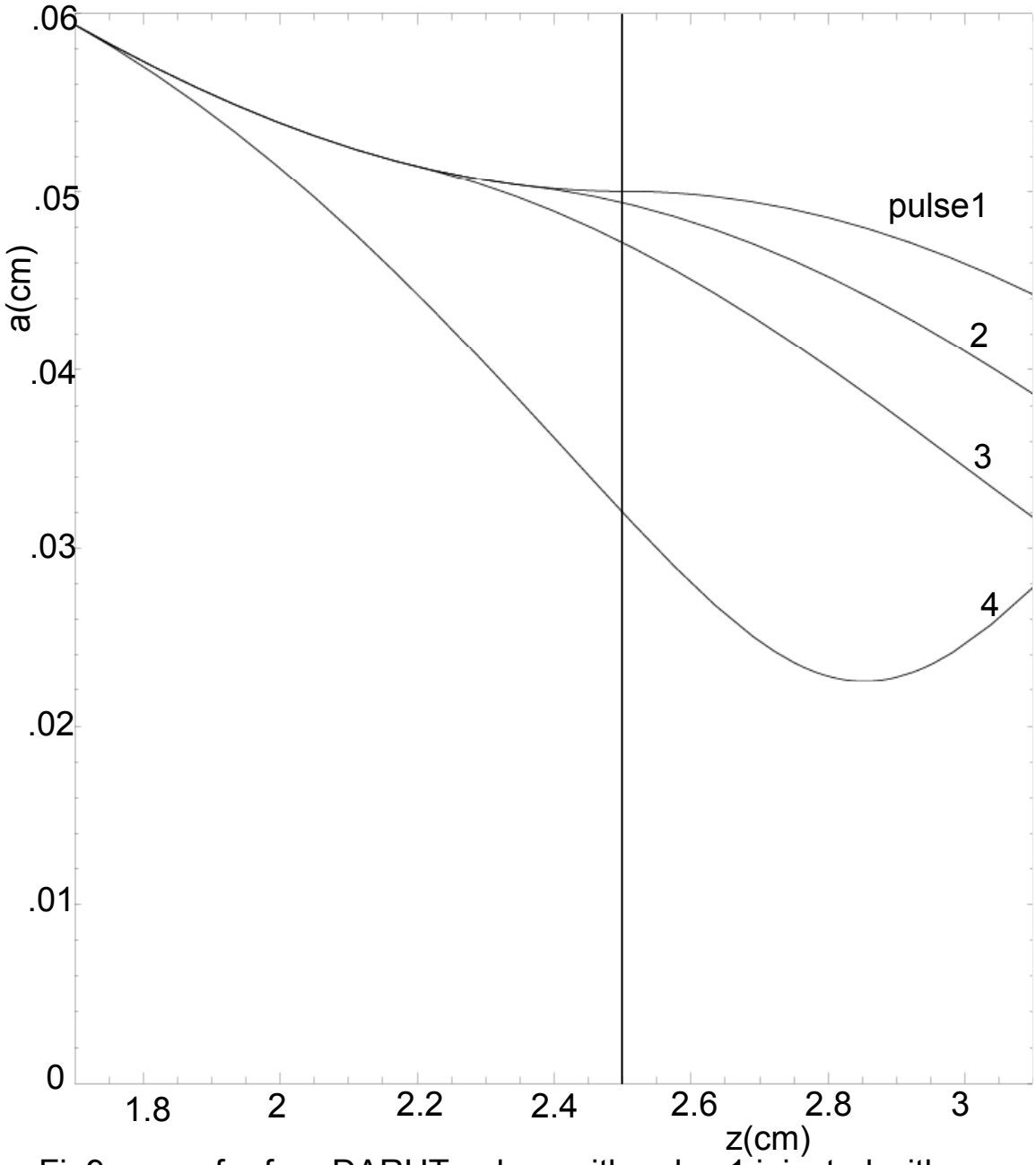

Fig9-a vs z for four DARHT pulses with pulse 1 injected with a[2.5]=.05 cm, a'[2.5]=0, low dose

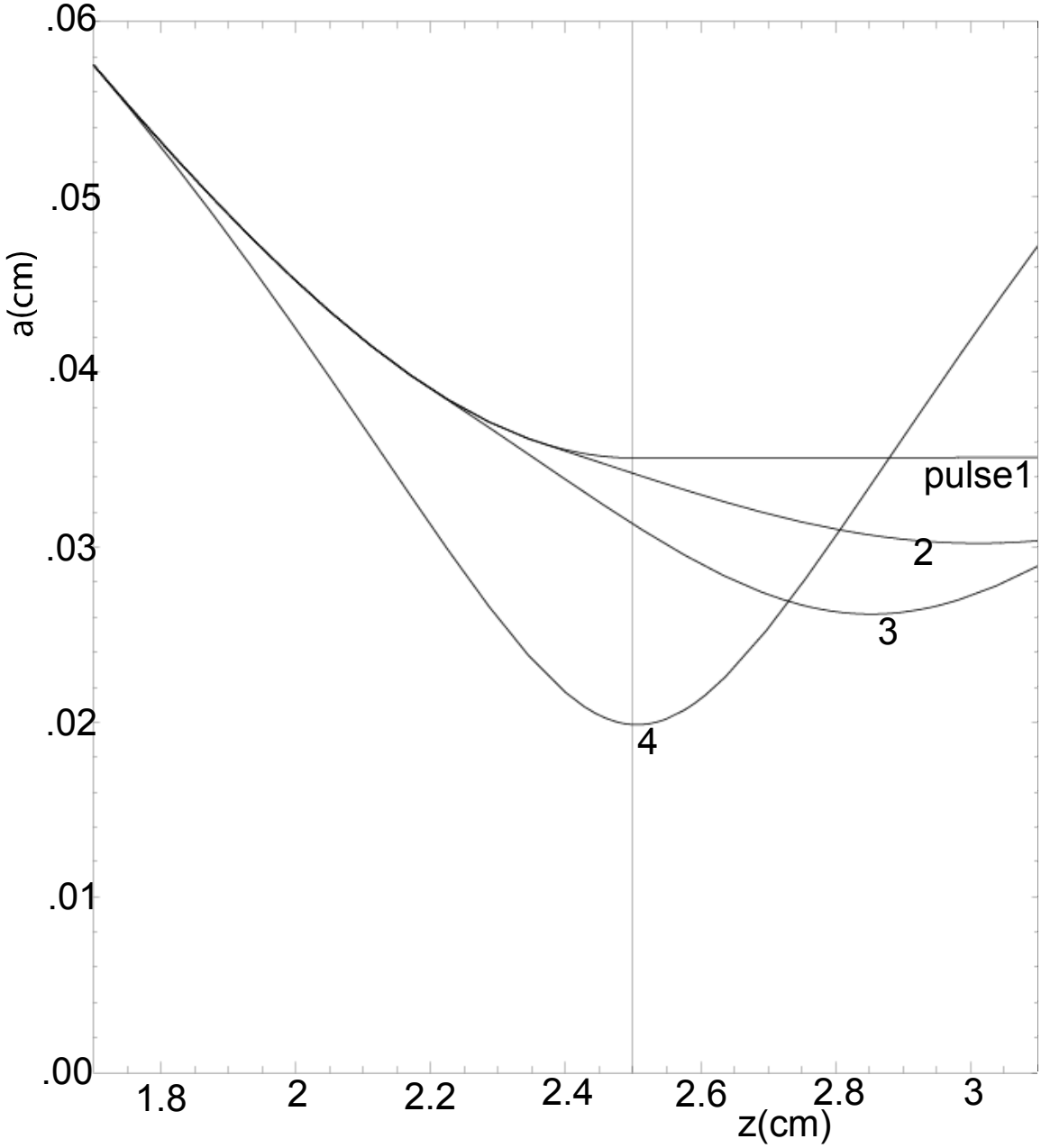

Fig 10-a vs z for four DARHT pulses with pulse 1 injected wi
a[2.5]=.0351 cm, a'[2.5]=0, low dose

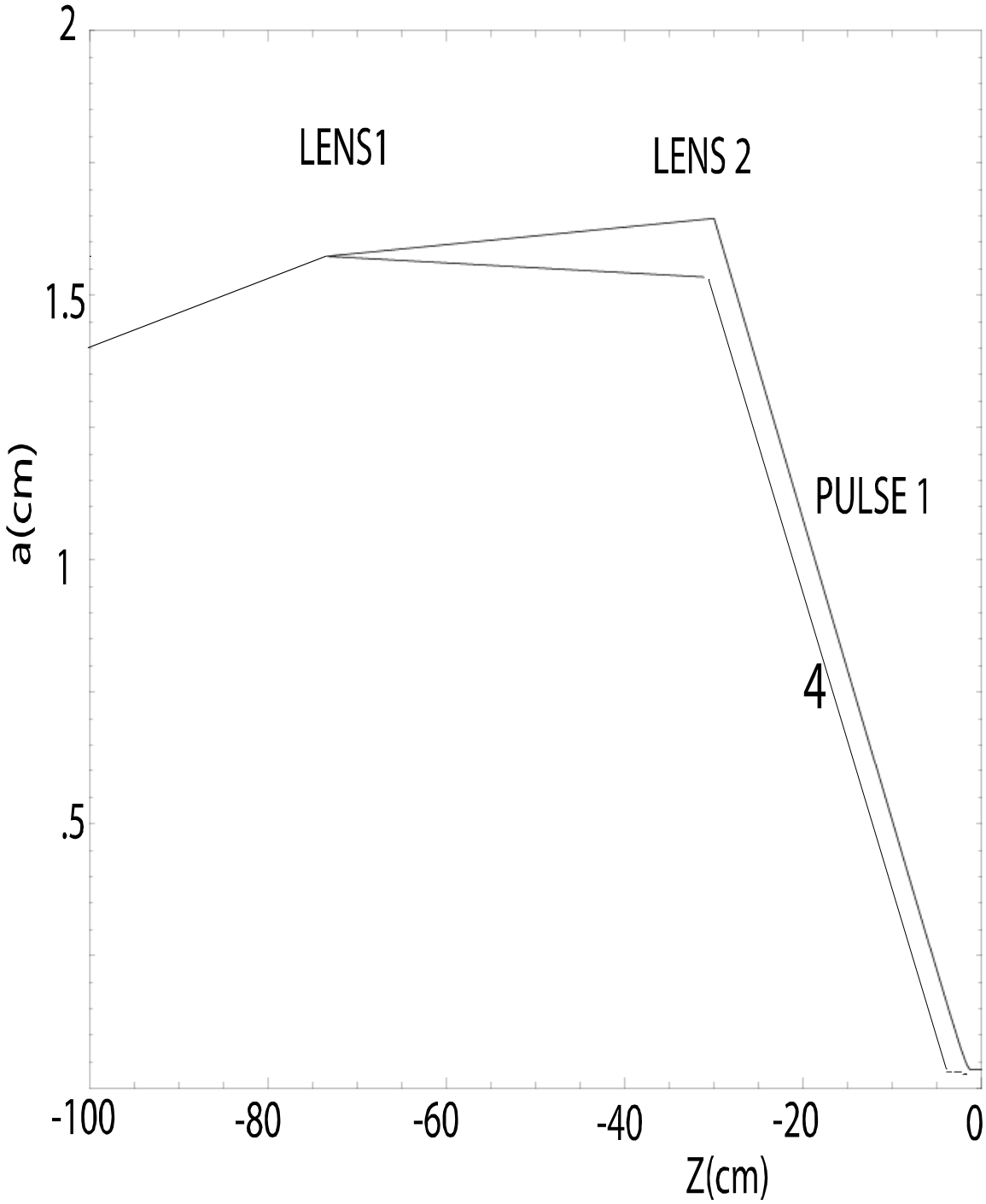

Fig11-Matching to equilibrium radius for different plume lengths using two fast lenses

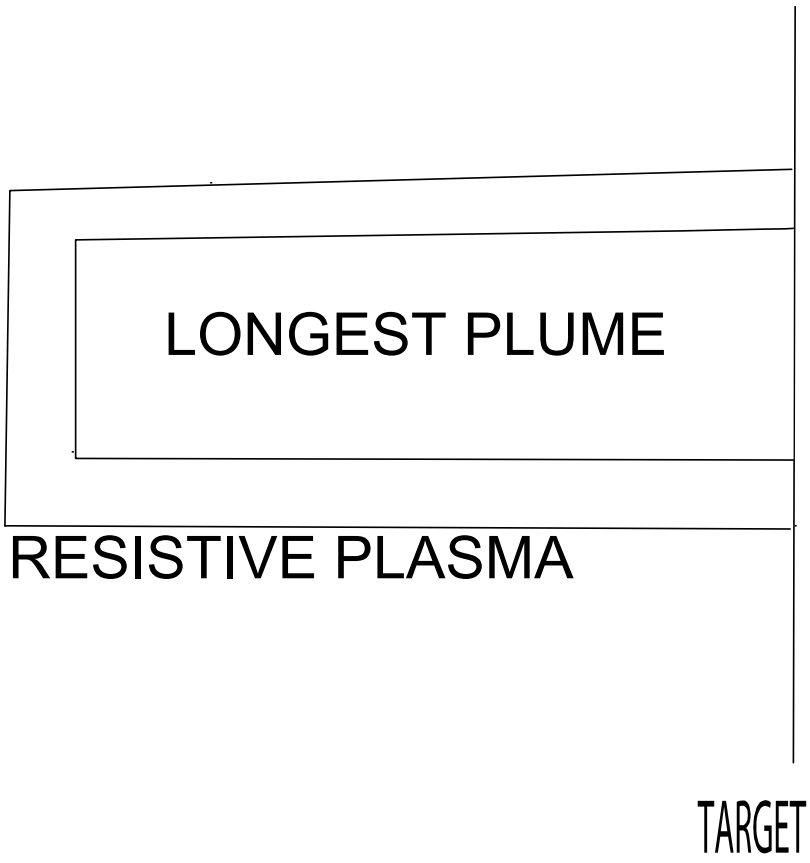

Fig 12-Resistive plasma with length longer than longest plume

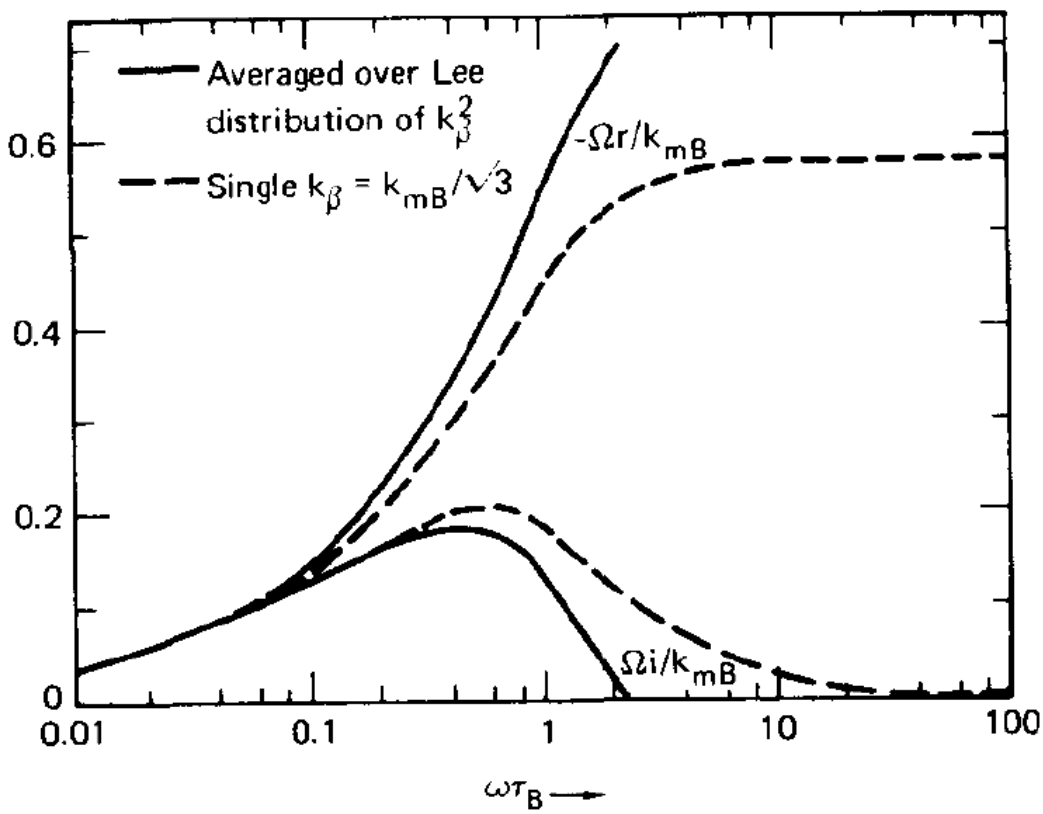

Fig 13-Hose instability growth rate