Stony Brook University

Self-injection process in laser-wakefield accelerator driven by CO_2 laser pulses

Arohi Jain, Irina Petrushina, Roman Samulyak, Vladimir Litvinenko, Navid Vafaei-Najafabadi*
Stony Brook University

John P. Palastro, Tanner T. Simpson
University of Rochester

Rafal Zgadzaj, Michael Downer
University of Texas at Austin

This work is supported by the following grants:
DoE grant DE-SC-0014043
DoE grant DE-SC-0020396
NERSC facility- DE-AC02-5CH11231

AAC 2022

November 8th, 2022

Introduction

- More efficient LWFA could be realized using long wavelength lasers-

  - For a fixed laser intensity I, lasers with longer wavelengths λ have larger ponderomotive potential ($\propto I\lambda^2$).
  - Stronger wakes can be generated at relatively low laser intensities which helps in ionization-based injection.

- We are trying to extend the work done on self-injection process in CO_2 driven wakes in the previous studies[1,2]

  - Investigating self-injection threshold
  - Performing PIC simulations for a range of CO_2 laser and plasma parameters using FBPIC[3]
  - Investigating cases for over matched, matched, and under matched spot sizes
  - Investigate variations of bubble size and shape associated with nonlinear evolution of the driving pulse result in self-injection of background plasma electrons.

[1] P. Kumar et al., Phys. Plasmas 28, 013102 (2021).
[2] E. Brunetti et al., Scientific reports 12, 6703 (2022).
[3] R. Lehe et al., Computer Phys. Comm. 203, 66–82 (2016).

Empirical threshold condition for self-injection

- In case of a non-evolving laser driver, for any given bubble wake velocity γ_0, self-injection occurs provided that the peak laser field strength is above a threshold, a_0^* [4]

$$a_0^* \approx 2.75\left[1 + \left(\frac{\gamma_0}{22}\right)^2\right]^{1/2}$$

n_e $(\times 10^{16}\mathrm{cm}^{-3})$	a_0^*
1	3.80
2	3.32
3	3.14
4	3.05
5	2.99

[4] C. Benedetti et al., Phys. Plasmas 20, 103108 (2013).

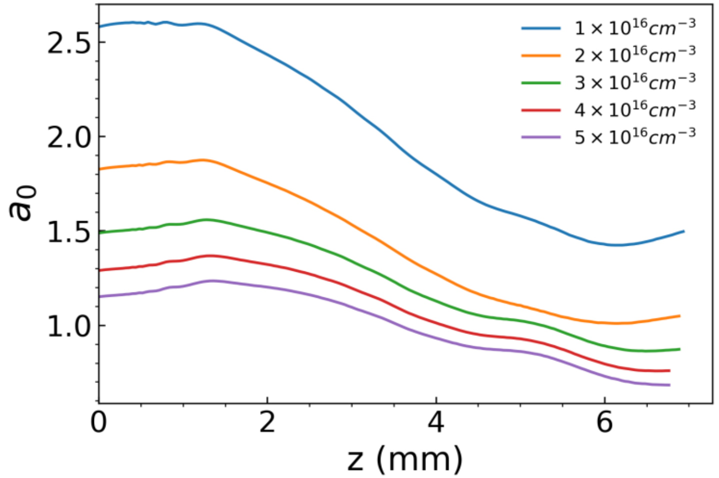
Parameter Scan

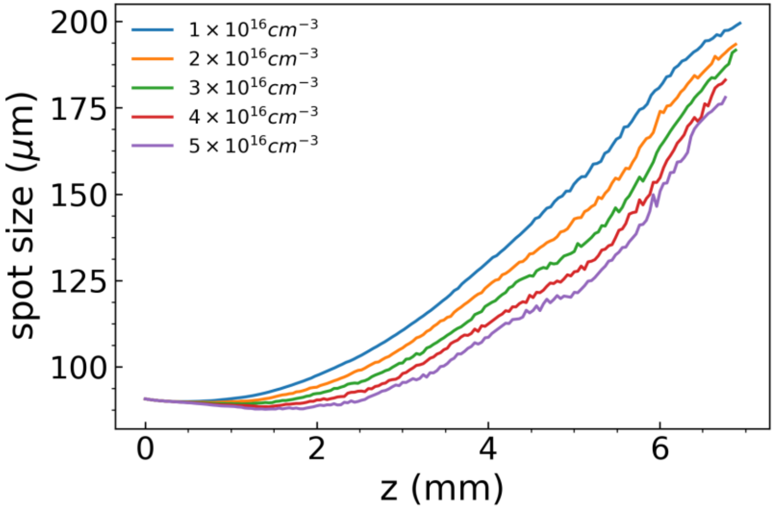
			$a < a_0^*$			$a > a_0^*$	
n_e $(\times 10^{16}\text{cm}^{-3})$	P_c (TW)	a_0^*	$a_0, w_m(\mu m)$ $(w_0 = 90\ \mu m, \boldsymbol{P = P_c/2})$	$a_0, w_m(\mu m)$ $(w_0 = 90\ \mu m, \boldsymbol{P = P_c})$	$a_0, w_m(\mu m)$ $(w_0 = 90\ \mu m, \boldsymbol{P = 2P_c})$	$a_0, w_m(\mu m)$ $(w_0 = 90\ \mu m, \boldsymbol{P = 2P_c})$	$a_0, w_m(\mu m)$ $(w_0 = 90\ \mu m, \boldsymbol{P = 3P_c})$
1	23	3.80	2.6, 145	3.67, 173		5.2, 205 (341 pC)	6.37, 227 (916 pC)
2	11.5	3.32	1.84, 87	2.6,103		3.7, 123 (40 pC)	4.5, 135 (330 pC)
3	7.7	3.14	1.5, 64	2.1, 75	3, 90		3.67, 100 (48 pC)
4	5.7	3.05	1.3, 51	1.82,61	2.6, 73		3.16, 80 (25 pC)
5	4.6	2.99	1.16, 43	1.64,52	2.32, 61		2.84, 65 (7pC)

No self-injection
Self-injection

Laser spot size w_0 and laser amplitude a_0 evolution

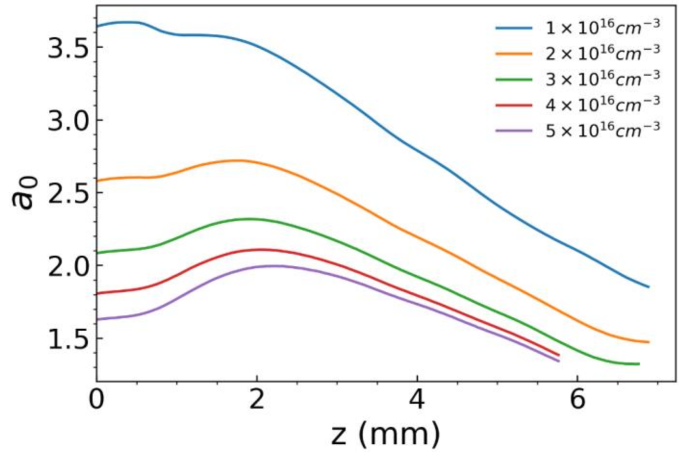
$$P = P_c/2$$

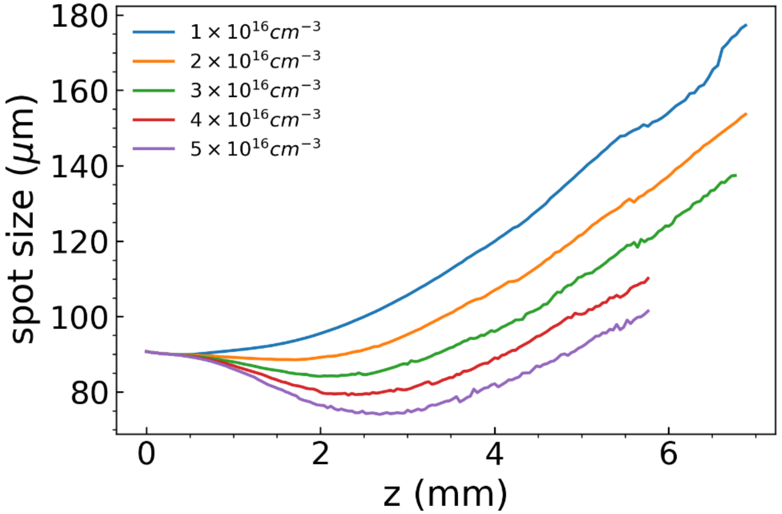




n_e $(\times 10^{16}\mathrm{cm}^{-3})$	a_0^*
1	3.80
2	3.32
3	3.14
4	3.05
5	2.99

$$P = P_c$$

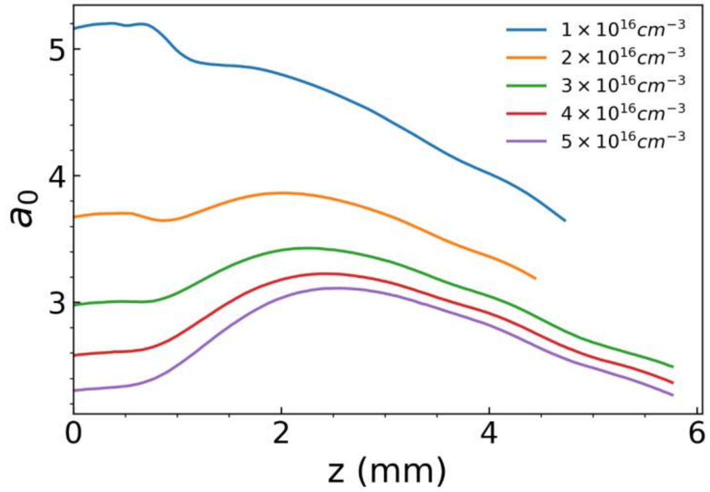


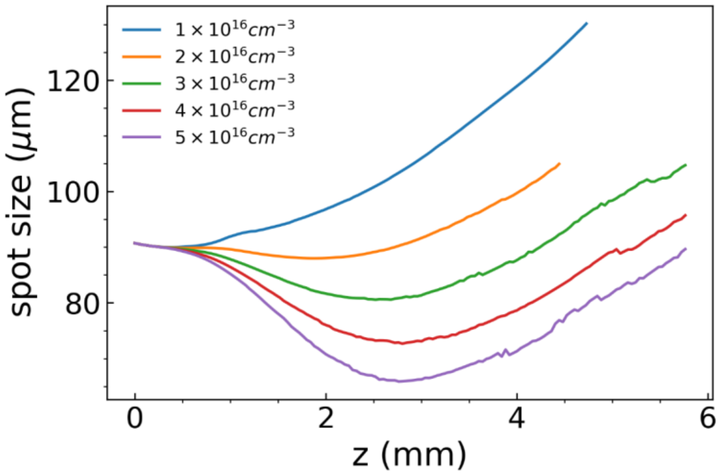


- **a_0 is below the threshold for self-injection (a_0^*)**
- **No injection is observed in CO_2 driven wakes for all the cases.**

Laser spot size w_0 and laser amplitude a_0 evolution

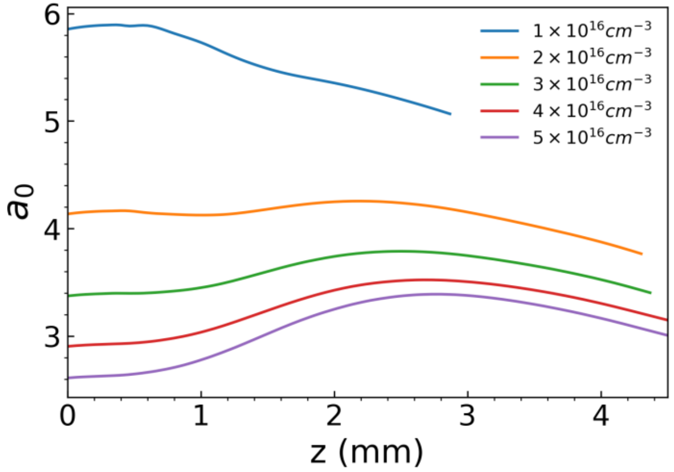
$P = 2P_c$

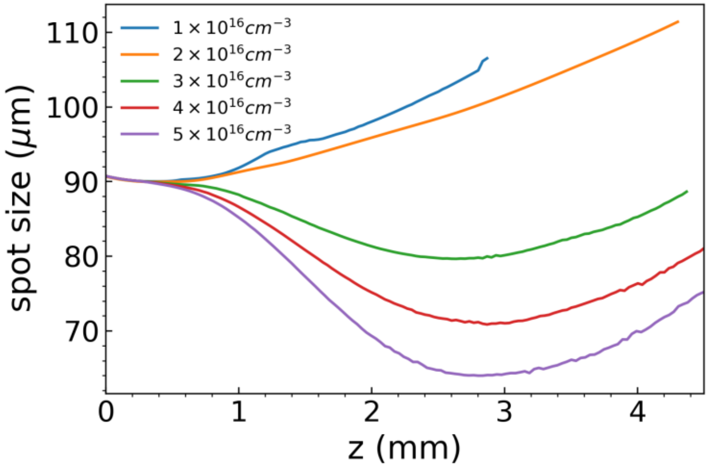




n_e ($\times 10^{16}\mathrm{cm}^{-3}$)	a_0^*
1	3.80
2	3.32
3	3.14
4	3.05
5	2.99

$P = 3P_c$

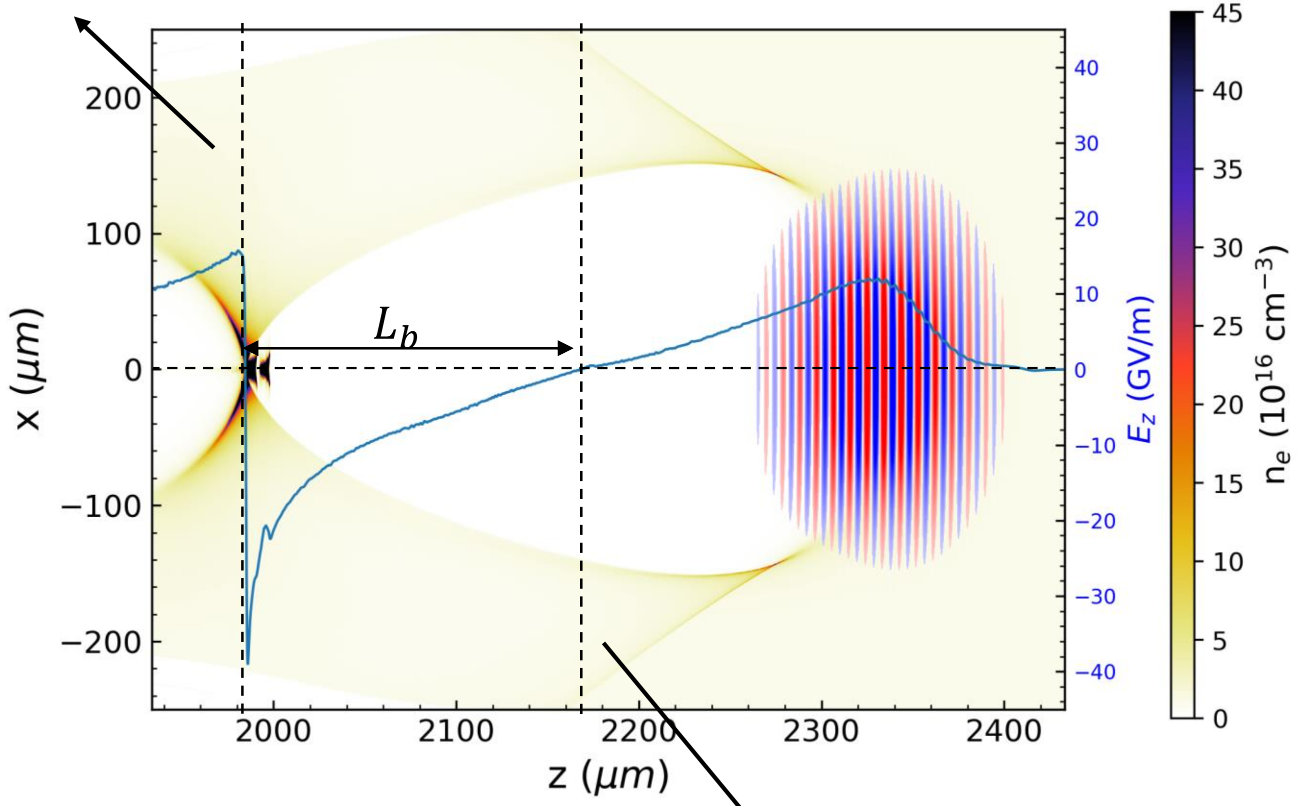




- $P = 2P_c$ – Injection suppresses for a_0 below self-injection threshold (a_0^*)
- Simulation results show good agreement with the empirical formula.

Method for calculating bubble velocity β_b, dephasing velocity β_d, and rate of change in bubble length $\partial L_b/\partial z$

Variotion of this point where $E_z = 0$ is used to calculate bubble velocity at the back β_b



Variation in the position of dephasing point where $E_z = 0$- used to calculate β_d

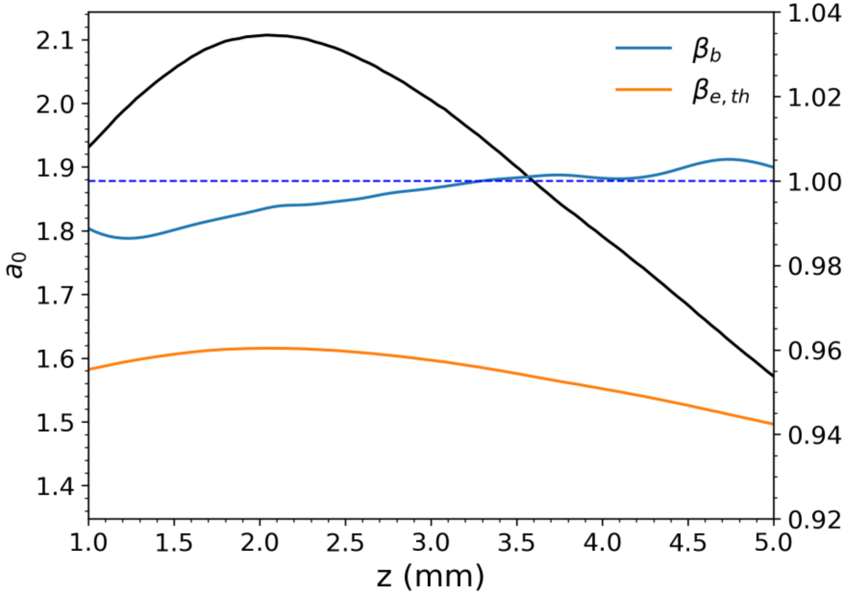
Electron energy relation with laser intensity

- Approximate total energy of the electron γ_e scattered by laser pulse derived using integration of the ponderomotive force averaged over the fast oscillatory motion[5]:

$$\gamma_e \sim 2\left(1+\frac{a^2}{2}\right)^{1/2} \rightarrow \beta_e = \left(1-\frac{1}{\gamma_e^2}\right)^{1/2}$$

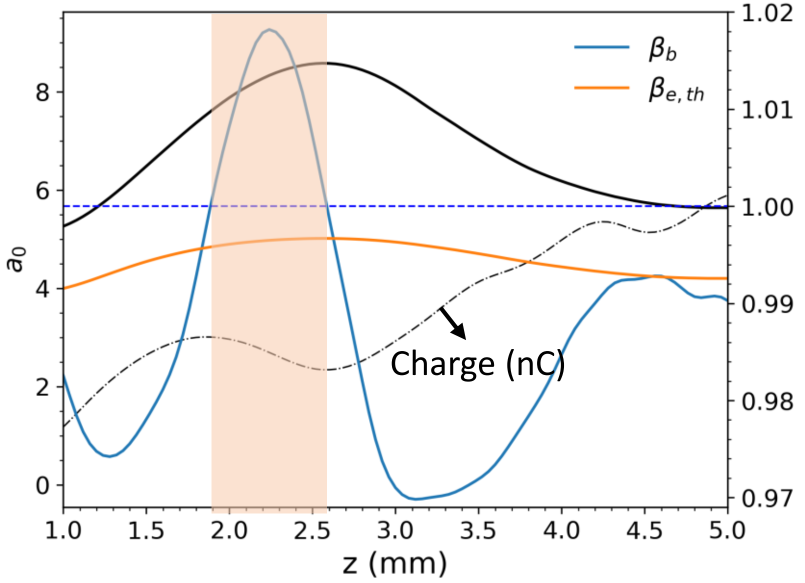
$a = \frac{eE_0}{m\omega c}$ is normalized laser amplitude

$P = 5.7\,TW,\ n_e = 4 \times 10^{16} cm^{-3}$



No self-injection

$P = 46\,TW,\ n_e = 1 \times 10^{16} cm^{-3}$



Self-injection

- **Velocity imparted to electrons β_e by laser pulse decreases with laser amplitude a_0- $a_0 \uparrow \beta_e \uparrow, a_0 \downarrow \beta_e \downarrow$**
- **No charge injection - bubble velocity at the back $\beta_b >$ velocity of the electron β_e**

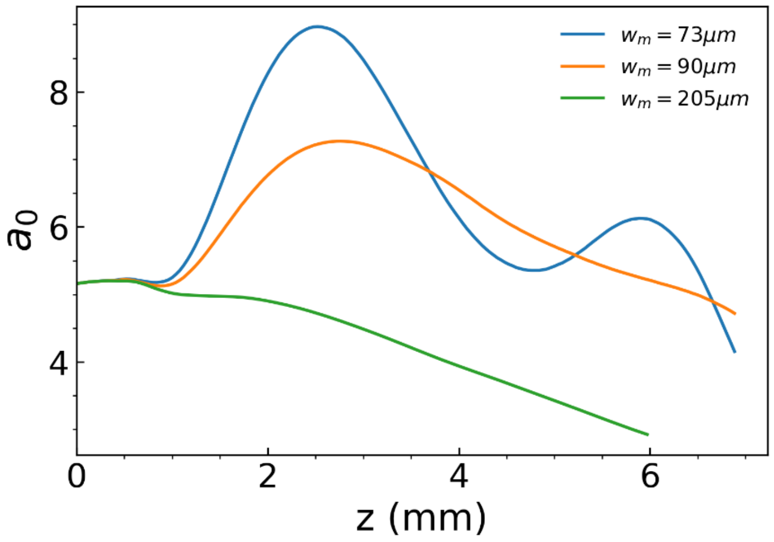
[5] M.P. Tooley et al., Phys. Rev. Lett. 110, 135002 (2013).

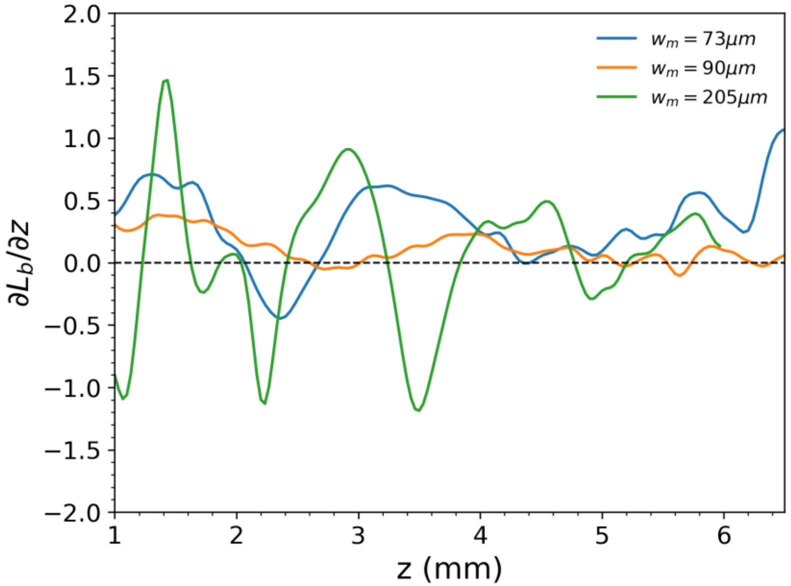
Study of self-injection with same peak power of CO_2 laser pulses for different cases

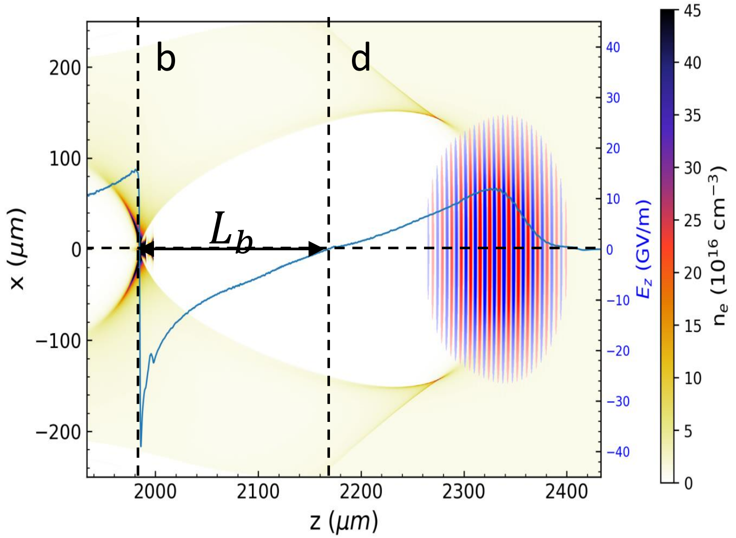
	n_e $(\times 10^{16}\mathrm{cm}^{-3})$	P_c (TW)	$a_0, w_0(\mu m)$, $P\ (TW)$	$w_m(\mu m)$	a_0^*	Injected charge (nC)
Over matched	7.9	2.9	5.2,90, 46	73	2.90	8.4
Matched	5.2	4.2	5.2,90, 46	90	2.98	3.7
Under matched	1	11.5	5.2,90, 46	205	3.8	0.37

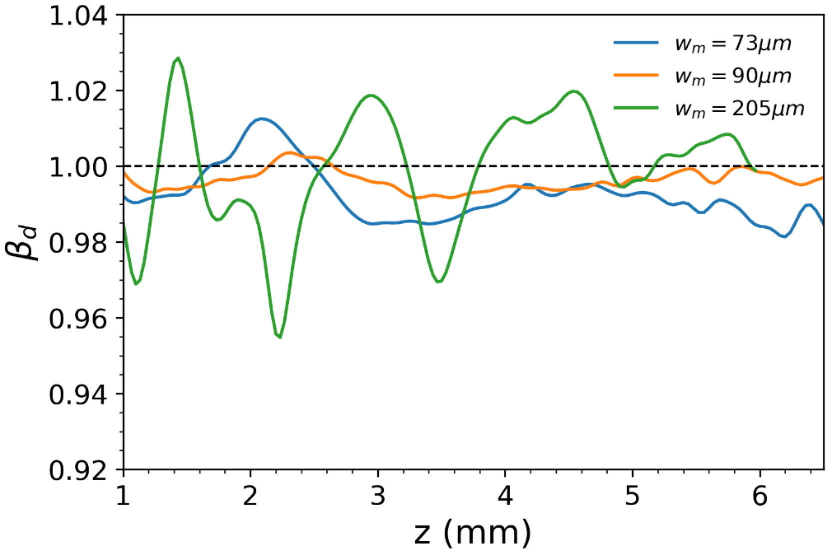
Laser amplitude is above the threshold for self-injection

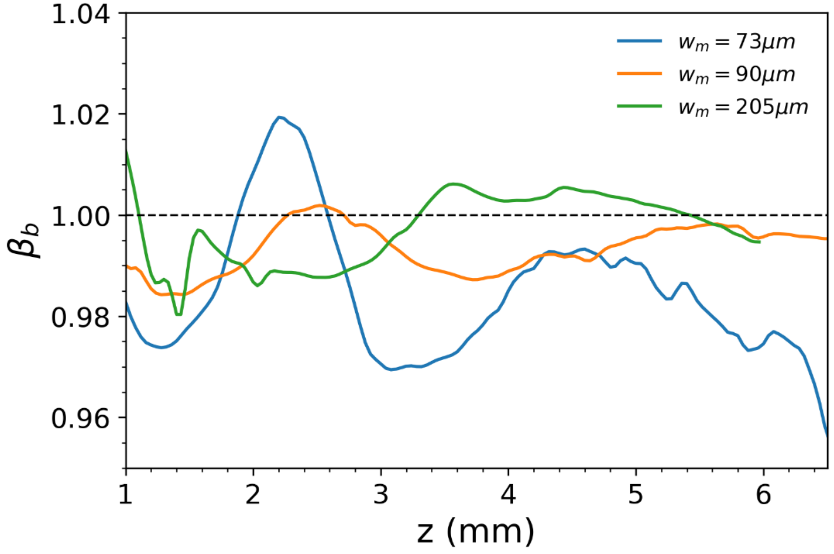
Evolution of the bubble











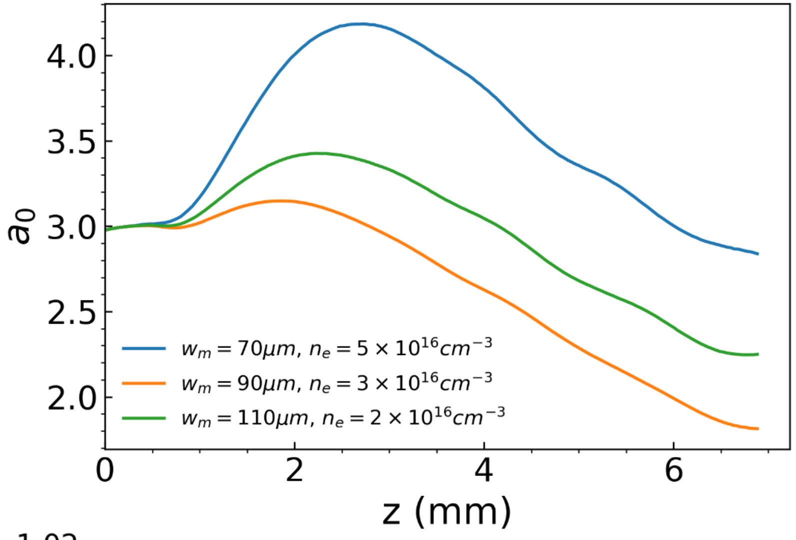
- **There is less variation in the rate of change in bubble length for the matched case $w_m = 90\ \mu m$.**
- **Dephasing point is comparatively stable for the matched case.**

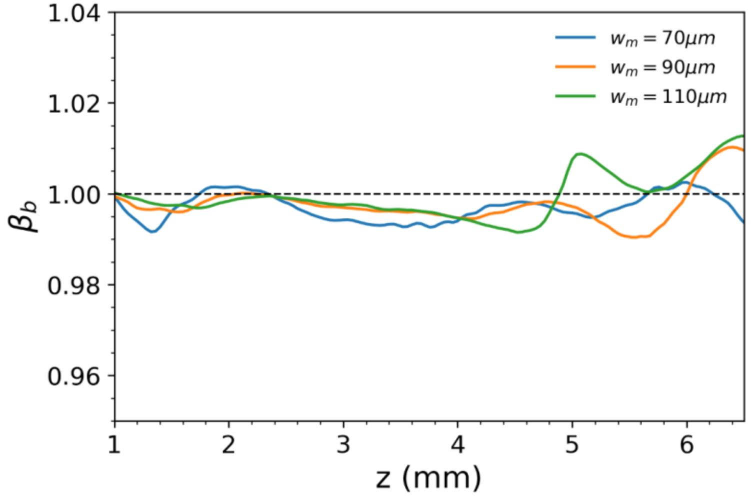
Study of self-injection with same peak power of CO_2 laser pulses for different cases

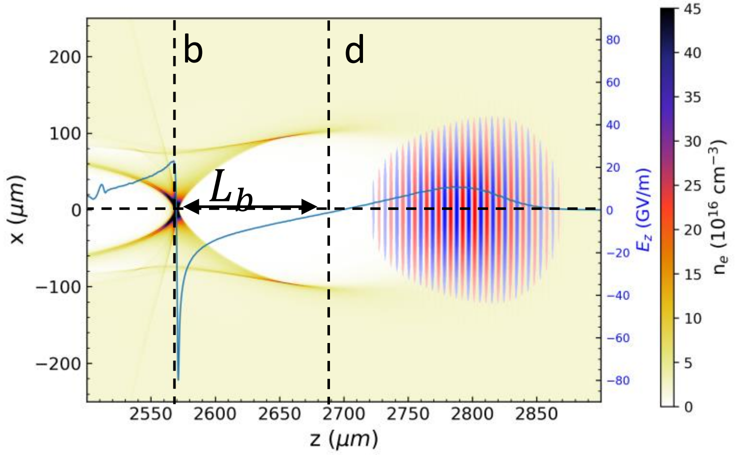
	n_e $(\times 10^{16}\mathrm{cm}^{-3})$	P_c (TW)	$a_0, w_0(\mu m)$, $P\ (TW)$	$w_m(\mu m)$	a_0^*	Injected charge (nC)
Over matched	5	4.6	3,90, 15.4	70	2.99	0.209
Matched	3	7.7	3,90, 15.4	90	3.14	No self-injection
Under matched	2	11.5	3,90, 15.4	110	3.32	No self-injection

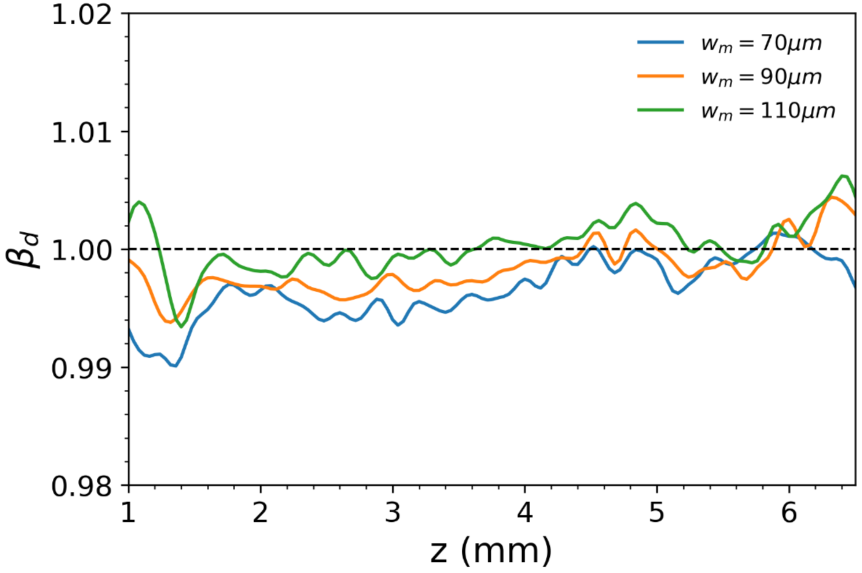
- **Laser amplitude is above the self-injection threshold for over matched case**
- **Laser amplitude is below the self-injection threshold for matched and under matched cases**

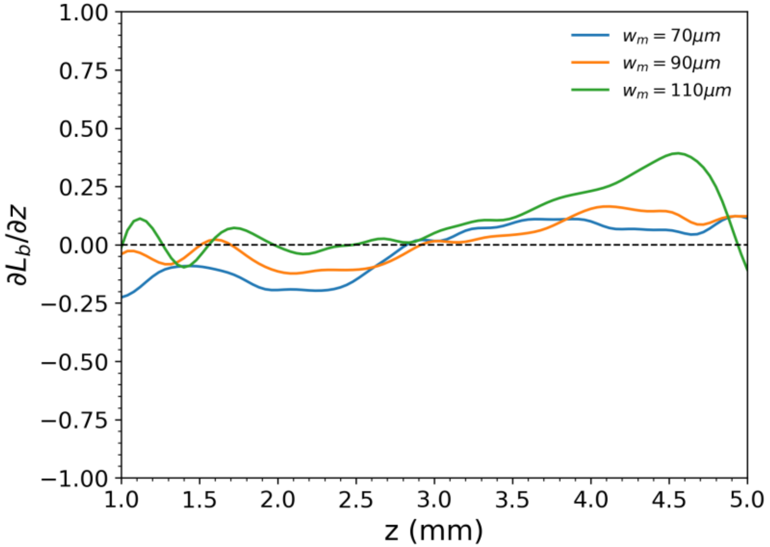
Evolution of the bubble





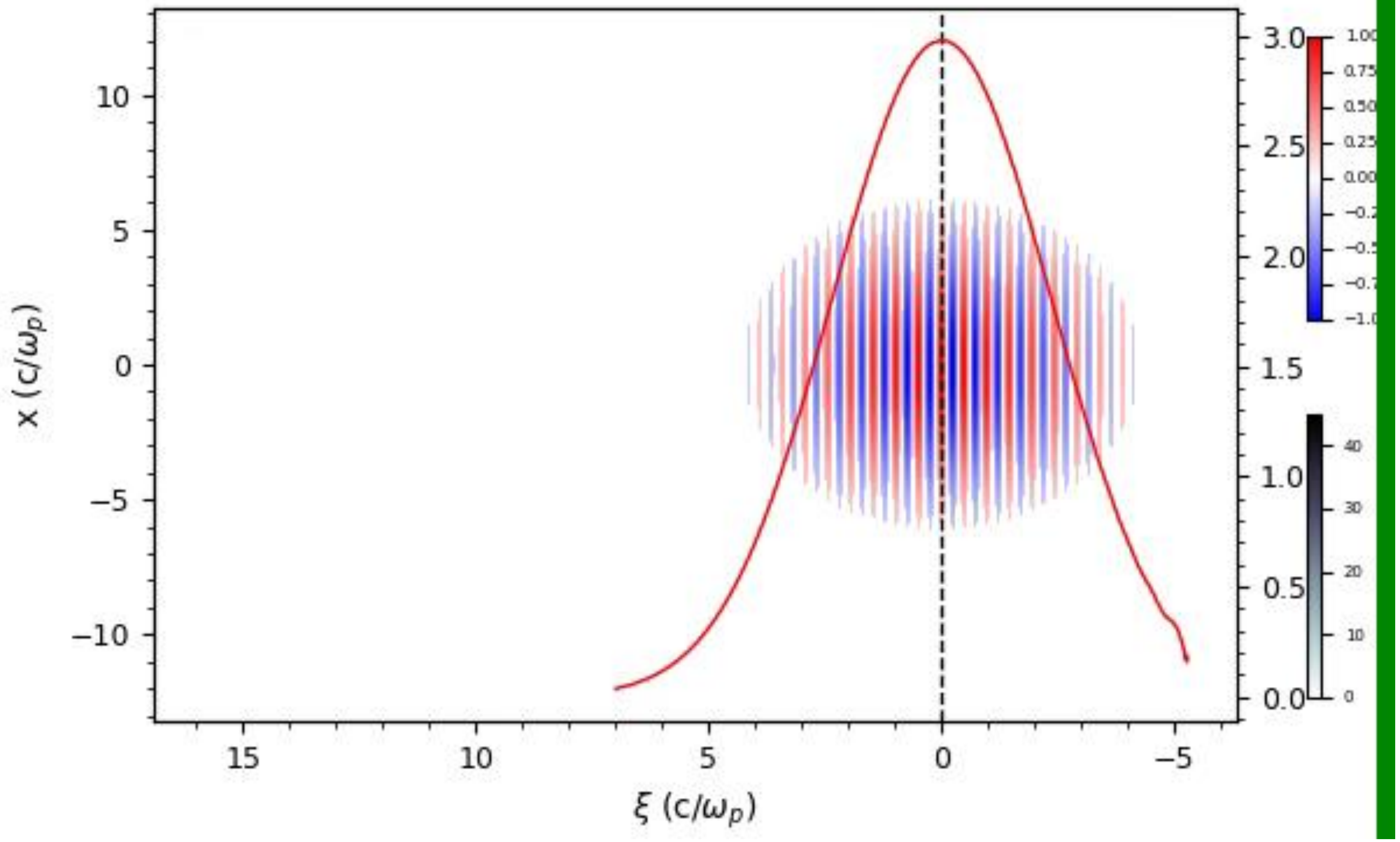






- **Back bubble velocity is comparatively stable for the matched case $w_m = 90\ \mu m$.**
- **Dephasing point is comparatively stable for the matched case $w_m = 90\ \mu m$.**
- **There is less variation in the rate of change in bubble length for the matched case.**

Evolution of bubble for the matched case



E_x

n_e

Stable bubble evolution in 6mm plasma

$a_0 = 3, P = 15.4\ TW, \lambda_0 = 9.2\ \mu m, \tau = 0.25$ ps, $w_0 = 90\ \mu m$

Conclusion

- There is a good agreement between simulation results and empirical formula for the self-injection threshold- to suppress self-injection $a_0 < a_0^*$.
- There is strong correlation between injected charge and back of the bubble velocity- no self-injection for $\beta_b > \beta_e$.
- Comparatively stable bubble evolution for the matched case.
- We report a parameter range that suppresses self-injection in fully blown-out bubbles which is an essential requirement in the experiments of controlled injection in LWFA.

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Thank you

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