Analysis of mobile ions in the *extreme regime* of *intense electron beams* in plasma wake-field accelerators

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Agenda

- The problem of ***mobile ions***
- Is ***driving*** or ***witness beam*** more problematic?
- Using heavy ions: ***Lithium***, ***Argon*** or ***Xenon***?
- Multiple Ionization and Trapped electrons

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Motivation

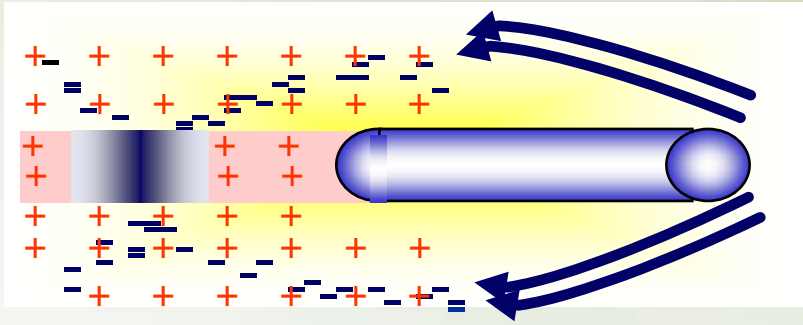
Present beams

$$\varepsilon_N \approx 1mm - mrad$$

$$\gamma \sim 10^5$$

$$\sigma^2_{matched} = \varepsilon_N \sqrt{\frac{2}{\gamma}} \frac{c}{\omega_p}$$

$$\sigma_{matched} \sim 1 - 2\mu m$$



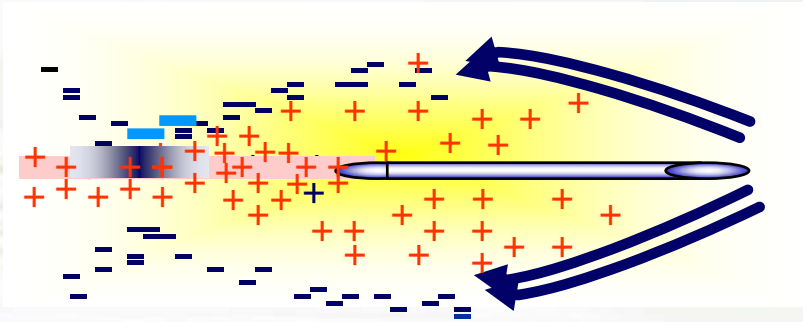
Ions do not move much

Future Collider

$$\varepsilon_N \approx 0.1mm - mrad$$

$$\gamma \sim 10^6$$

$$\sigma_{matched} \sim 0.3\mu m$$



Ions sucked in by dense beam
Focusing no longer constant & linear

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Ion Motion

$$E_{rb} = -2\pi e n_b r$$

$$= \frac{-2\pi r N_b}{(2\pi)^{3/2}\sigma_r^{\,2}\sigma_z}$$

Electric Field of the electron Beam

$$\frac{d^2 r}{dt^2} = \frac{Ze(-E_{rb} + E_{ri})}{Am_a} = -\frac{Ze^2}{Am_a}\left(\frac{N_b}{\sqrt{2\pi}\sigma_r^{\,2}\sigma_z} r - \frac{\delta}{r}\right)$$

$$\frac{d^2 r}{dt^2} \square -k_i^{\,2} r$$

Equation of motion for Ions

$$\Delta\varphi = k_i\sqrt{2\pi}\sigma_z$$

Ions Phase advance after 1 beam length

-S. Lee, et al., AAC: Eighth Workshop
-J.B. Rosenzweig, et al., PRL 95, 2005

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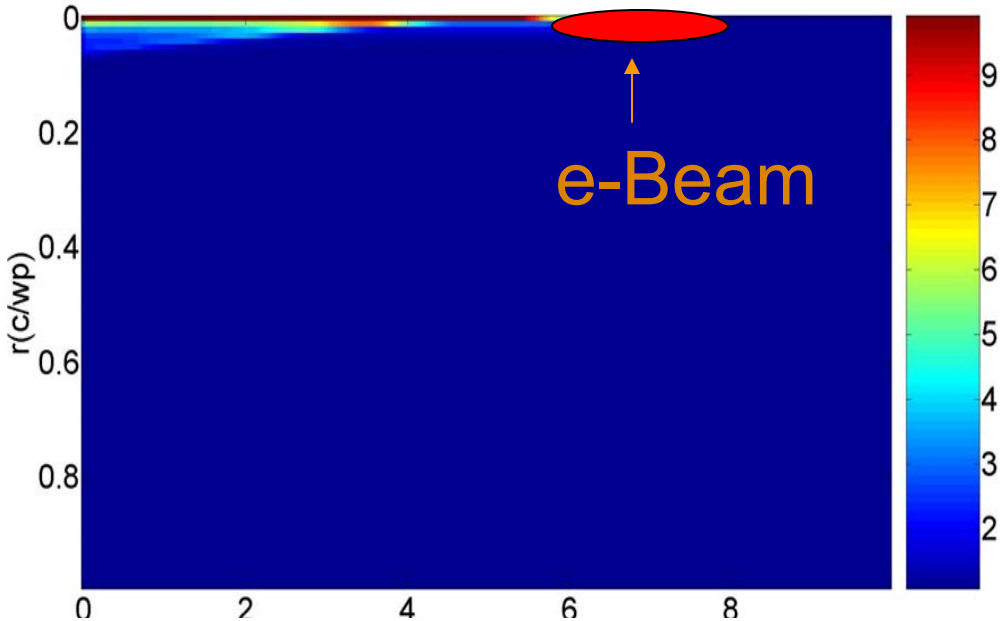

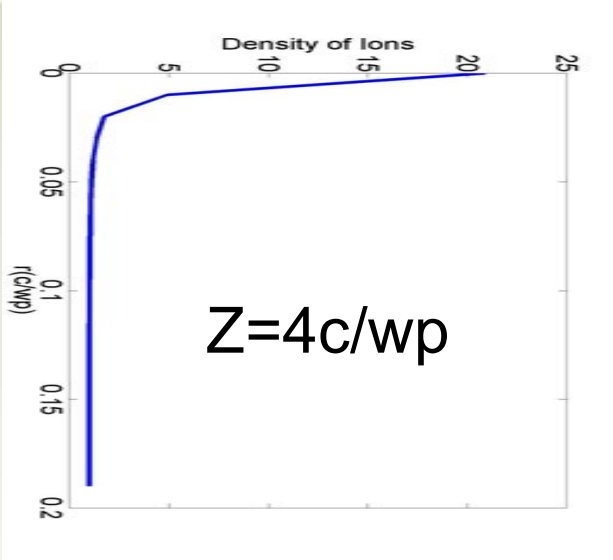

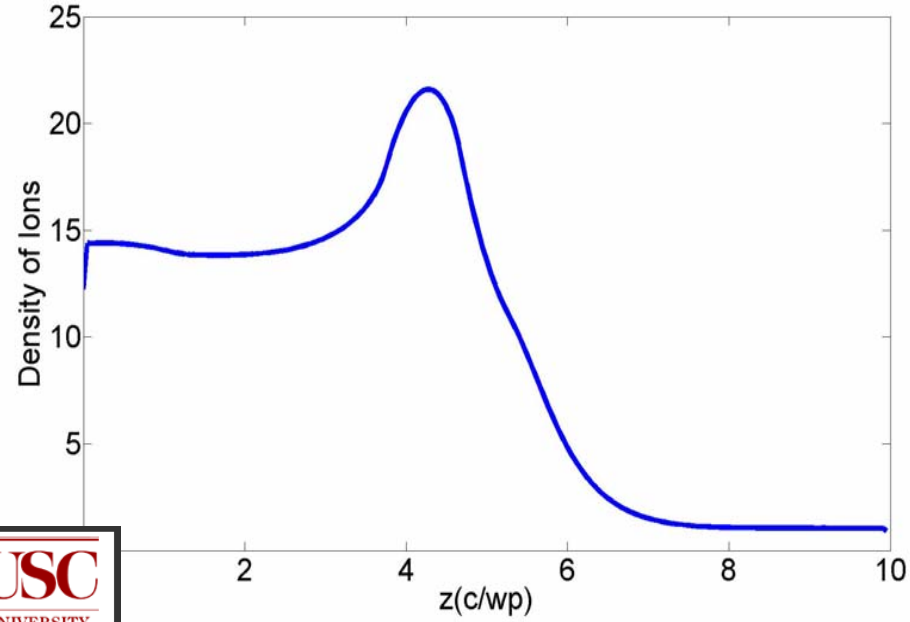

$Hydrogen:$

$n_o = 10^{16} cm^{-3}$

$Beam:$

$\sigma_r = 13 \mu m$

$\sigma_z = 35 \mu m$

$N_b = 1.5 \times 10^{10}$

$250 GeV$

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$$\Delta\varphi = \frac{\pi}{2}$$ ***Total collapse***

	γ	ε_N	$\sigma_{matched-beam}$	$\Delta\varphi$
SLAC Experiment (50GeV)	10^5	$1mm-mrad$	$2\mu m$	***0.4*** **Insignificant**
Afterburner @ 125 GeV	2.5×10^5	$0.4mm-mrad$	$1\mu m$	***0.8*** ***Small***
Afterburner @ 500 GeV	10^6	$0.1mm-mrad$	$0.3\mu m$	***>2*** ***Large***

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Obvious Solutions:

- ***Larger spot size*** $\sigma_r \uparrow$
- ***Heavier ions*** $m_a \uparrow$

Synchrotron Radiation Limits maximum Drive Beam Spot Size

- **P** (synchrotron radiation) = $\frac{2}{3}\left(\frac{d\beta}{dt}\right)^2 \frac{e^2\gamma^4}{c}$

$$= c\, \mathbf{F_{drag}}$$

also $\frac{d\beta}{dt} = \frac{2\pi n_0 e^2 \sigma_r}{\gamma m c}$

- **E** (deceleration) = $\frac{1}{2}\frac{mc\omega_p}{e}$

In order to have low energy loss due to synchrotron radiation:

- $\mathbf{F_{drag}} < \mathbf{e\,E}$ $\quad \boxed{\Rightarrow \sigma_r < \sqrt{\frac{3m_e c^5}{\omega_p{}^3 e^2 \gamma^2}} \approx 30\mu m}$

(for 250GeV beam and $\omega p = 5.35 \times 10^{12}$)

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$$\Delta\varphi = k_i\sqrt{2\pi}\sigma_z = \sqrt{\frac{Ze^2 N_b \sqrt{2\pi}\sigma_z}{Am_a\sigma_r^{\ 2}}}$$

Phase Advance of mobile ions

	Drive Beam	Witness Beam
	$\sigma_r = 10\mu m$	$\sigma_r = 140nm$
Hydrogen (M=1)	Δφ=0.1	Δφ=6.45
Lithium (M=7)	Δφ=0.04	Δφ=2.44
Argon (M=40)	Δφ=0.015	Δφ=1
Xenon (M=132)	Δφ=0.009	Δφ=0.56

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Nuclear Scattering of the witness beam

$$\Delta(\gamma\varepsilon) = 4\pi N_a \frac{Z^2 r_e^2 \overline{\beta}}{G} \ln\left(\frac{\theta_{\max}}{\theta_{\min}}\right)\left(\sqrt{\frac{\gamma}{\gamma_i}} - 1\right)$$

$$\theta_{\max} = \frac{\overline{h}}{pR}$$ R= Nuclear radius

$$\theta_{\min} = \frac{\overline{h}}{p\lambda_D}$$ λ_D = Debye length

Lithium (M=1)	Δ(γε)>3% growth
Argon (M=40)	Δ(γε)>100% growth
Xenon (M=132)	Δ(γε)>1200% growth

G. Dugan "Advanced Accelerator System Requirements for future Linear colliders'

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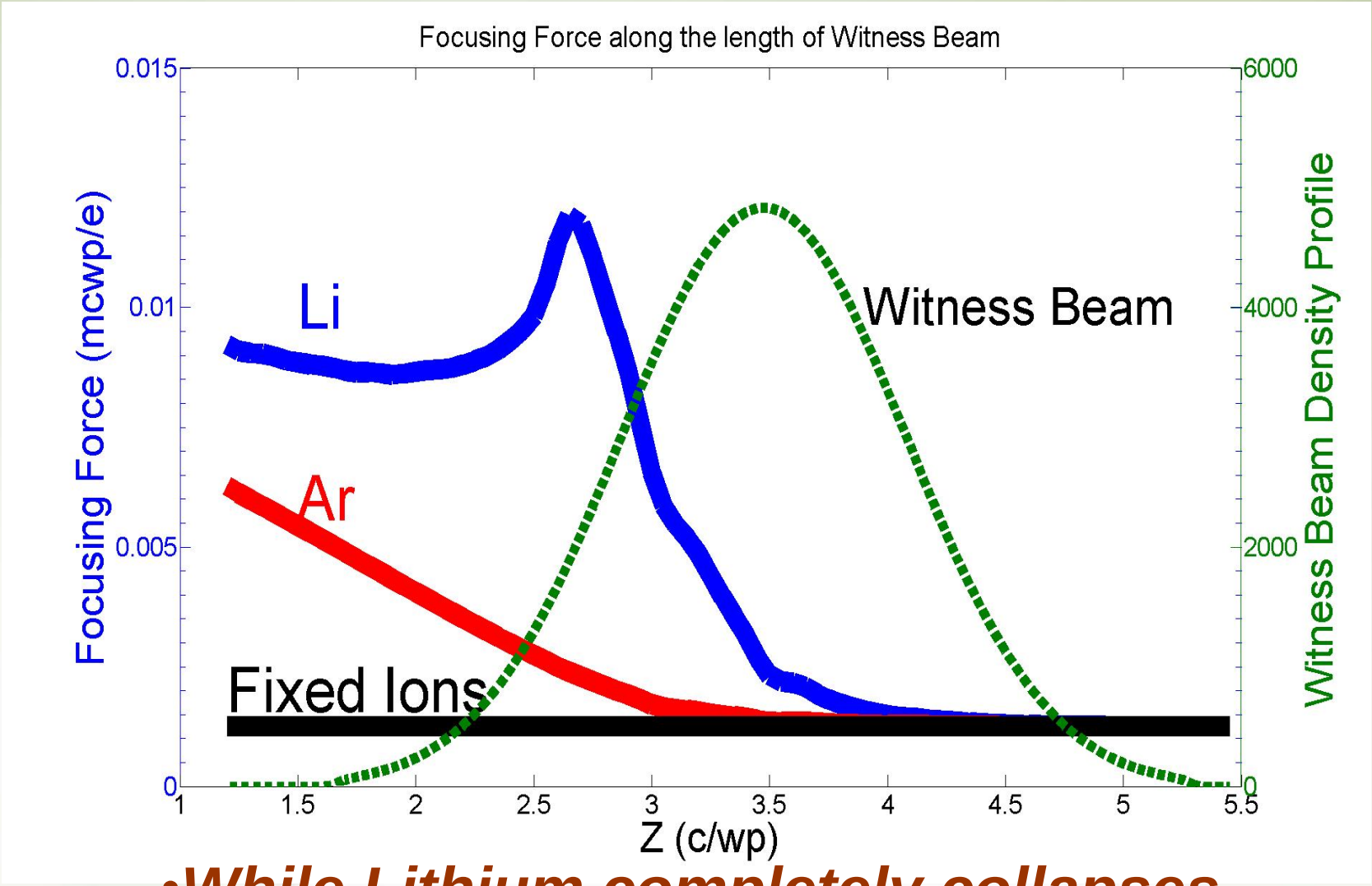
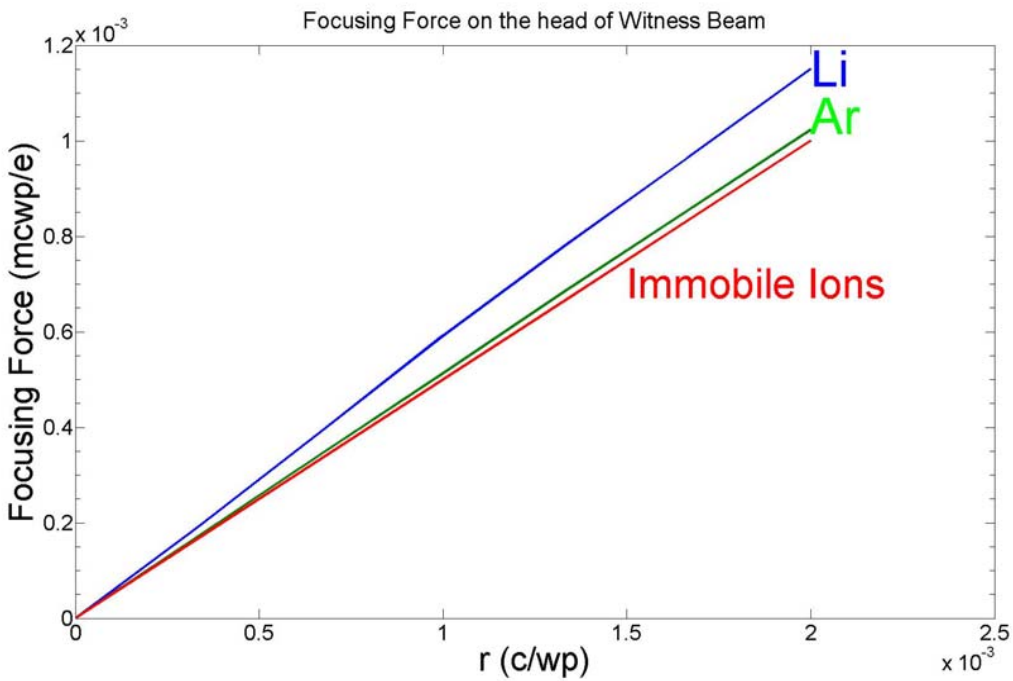
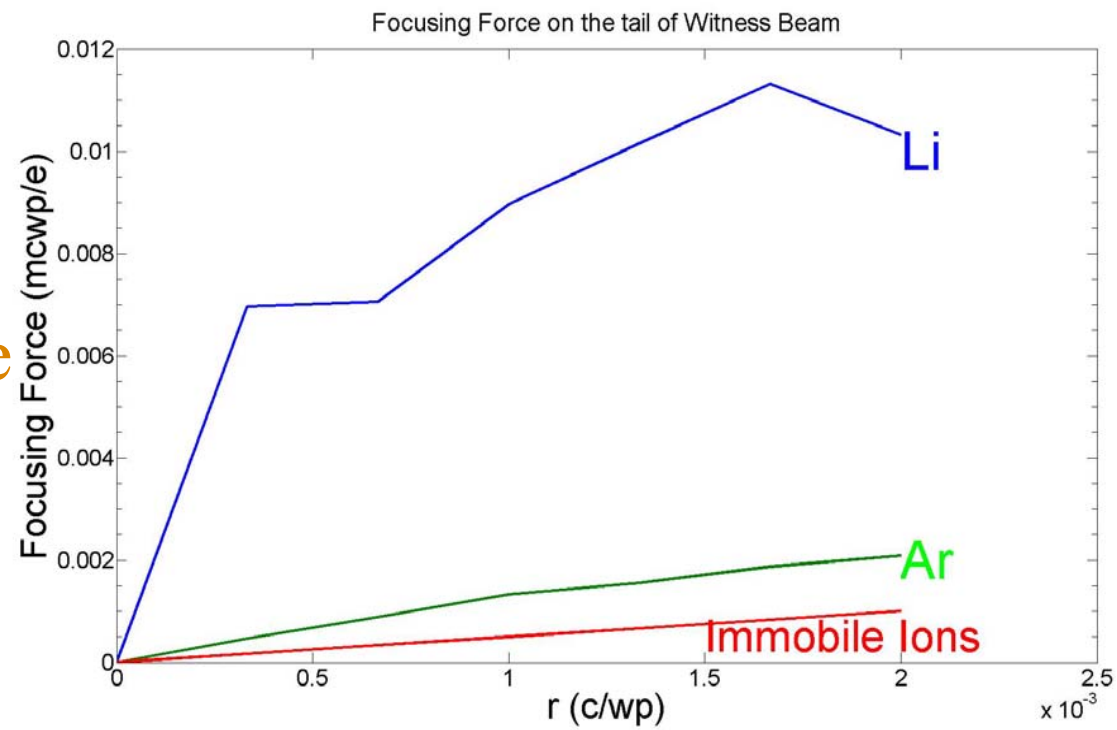


- ***While Lithium completely collapses before it reaches the tail, Argon's increase in Focusing Force is still acceptable***



Focusing Force on the head of Witness beam

Focusing Force on the tail of witness beam



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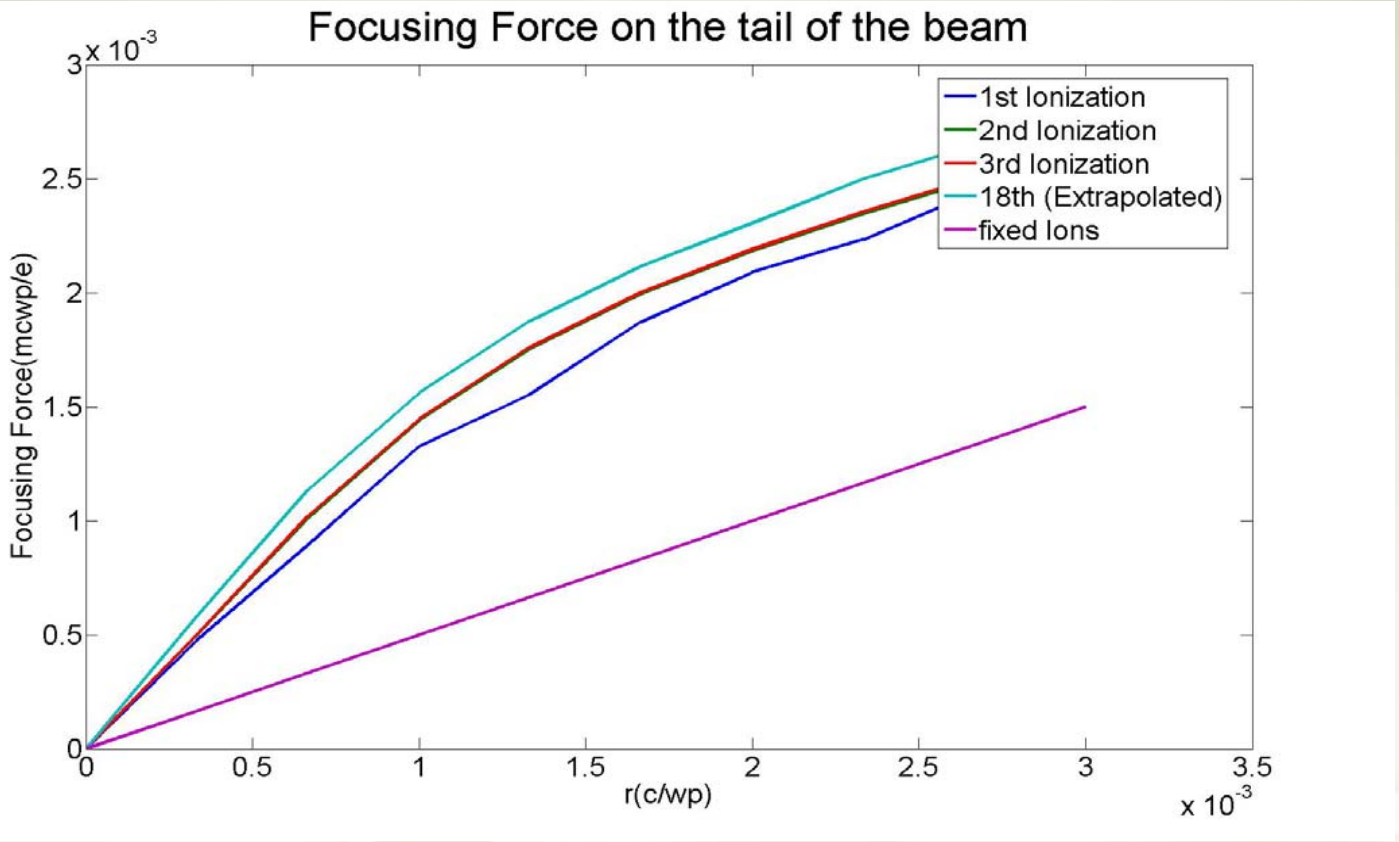
Multiple Ionization problem



- *Electric Field of Witness beam almost fully ionizes Argon but new-born ions do not have enough time to move*

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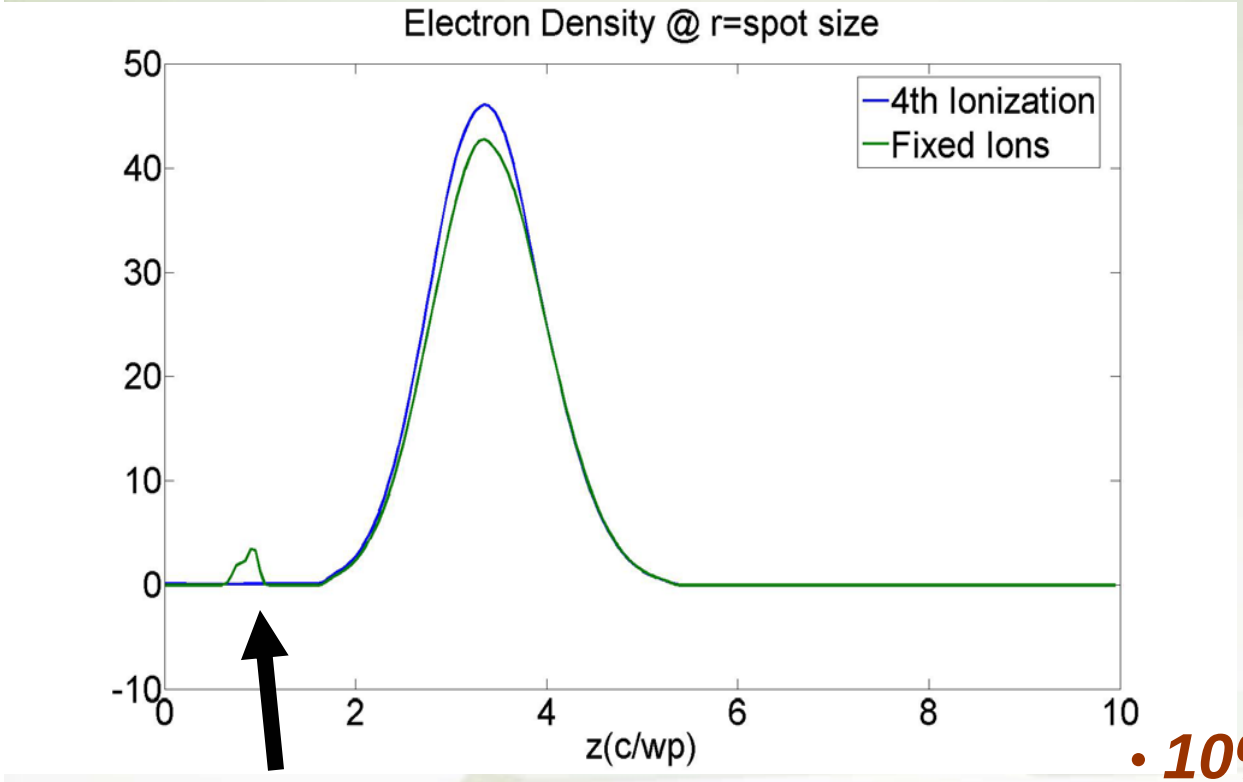
Trapped electrons load the wake



Plasma electrons overshoot the axis

- **10% beam loading effect due to ionization within the witness beam**
- **Affects the efficiency and energy spread**

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Conclusion

- The ion motion problem addressed
- Obvious Solutions:
  - Larger spot size
  - Heavier ions
- Synchrotron radiation
- Multiple ionization
- Nuclear scattering

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Thank you

Q&A

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