Physics of Trapping in Ultra Relativistic Plasma Wakes

E-164X, E-167 Collaboration

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Maximum Amplitude of a Plasma Wave: WAVE BREAKING (WB) in History

- **Akhiezer and Polovin, 1956** : 1-D relativistic cold WB

$$E = \sqrt{2}\sqrt{(\gamma_p - 1)}\,\frac{mc\omega_p}{e}$$

$$\approx 4.3\,TV/m \quad for\,\gamma_p = 10000,\ n_p = 10^{17}\,cm^{-3}$$

- **J. M. Dawson, 1959** : 1-D non-relativistic cold WB

$$E = \frac{mc\omega_p}{e}$$

$$\approx 37\,GV/m \ \ for\ n_p = 10^{17}\,cm^{-3}$$

Neighboring sheets cross, i.e. wave breaks and plasma electrons are self trapped

T. P. Coffey, 1971 : 1-D warm non-relativistic WB

T. C. Katsouleas, W. B. Mori
J. B. Rosenzweig, 1988 : 1-D warm relativistic

How about 3 D wave breaking limit?

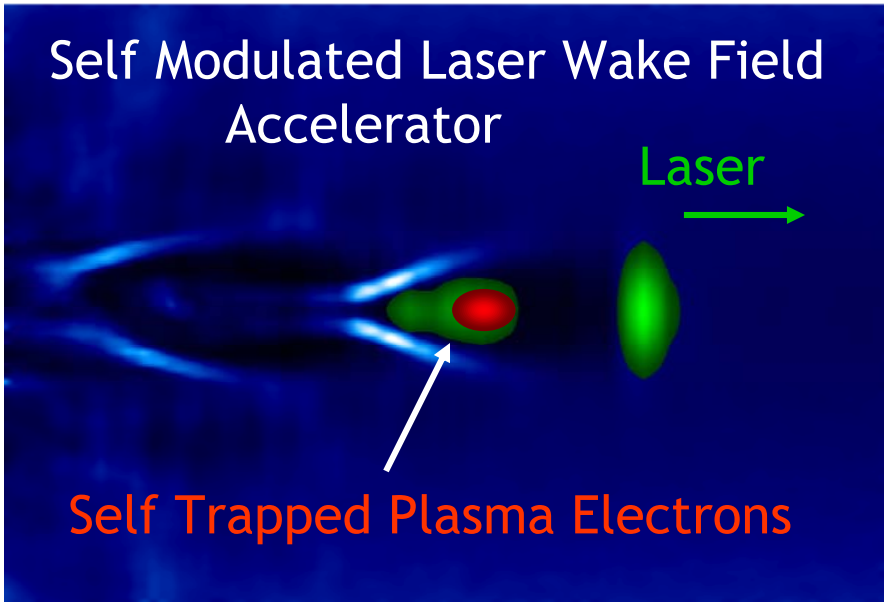
- No analytical expression exists

Do we need TV/m to trap?
Is wave breaking
the end of Plasma Accelerators?

Injection Mechanism for Laser Wake Field Experiments (LWFA): Trapping

- A peak field of 100 GV/m is enough to cause WB and self-trapping

- The wake grows from and instability, therefore the onset of trapping is not controllable



- What is the critical field for trapping ?

- Can we measure it?

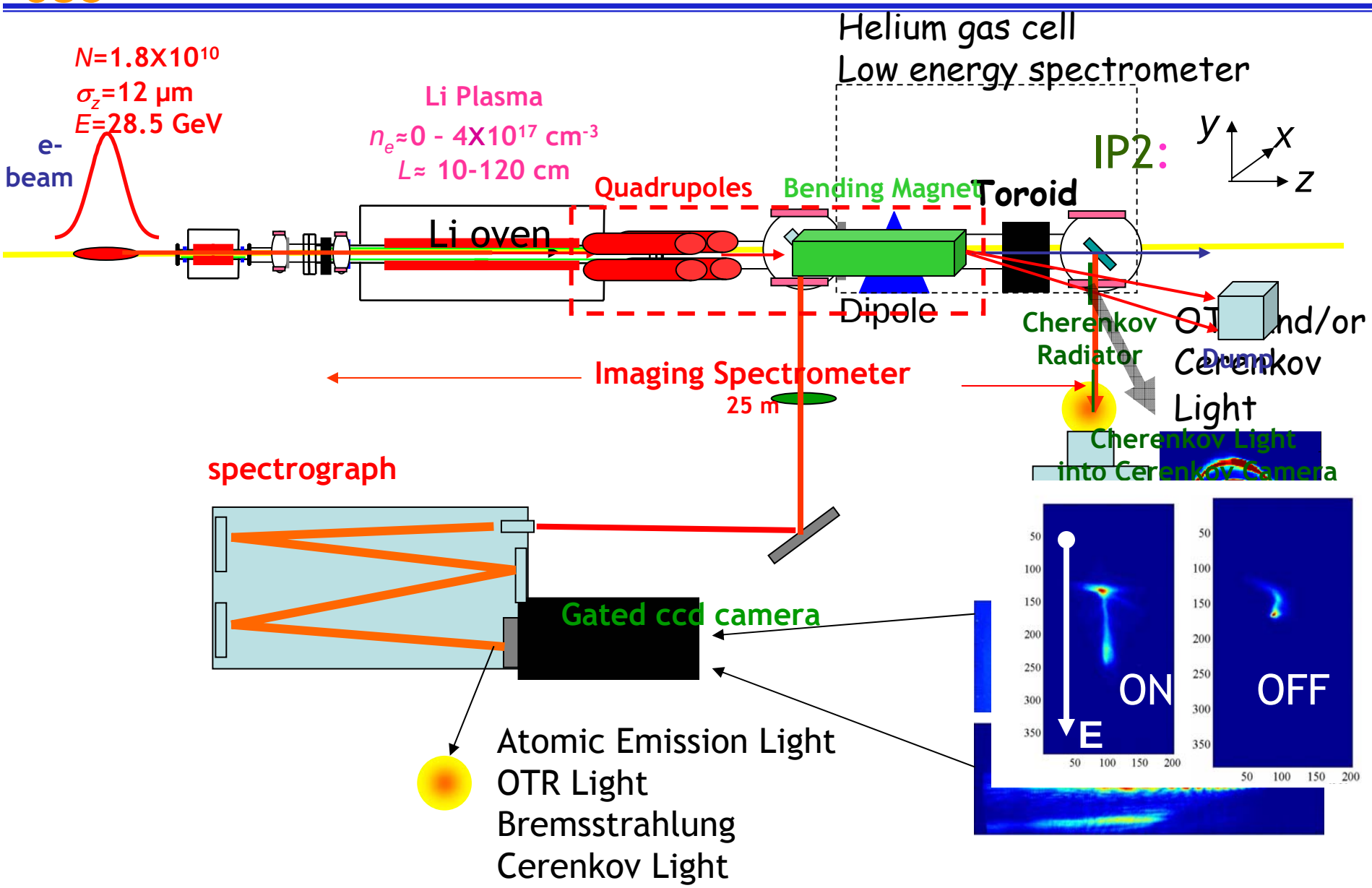
- Can we write an analytical expression?

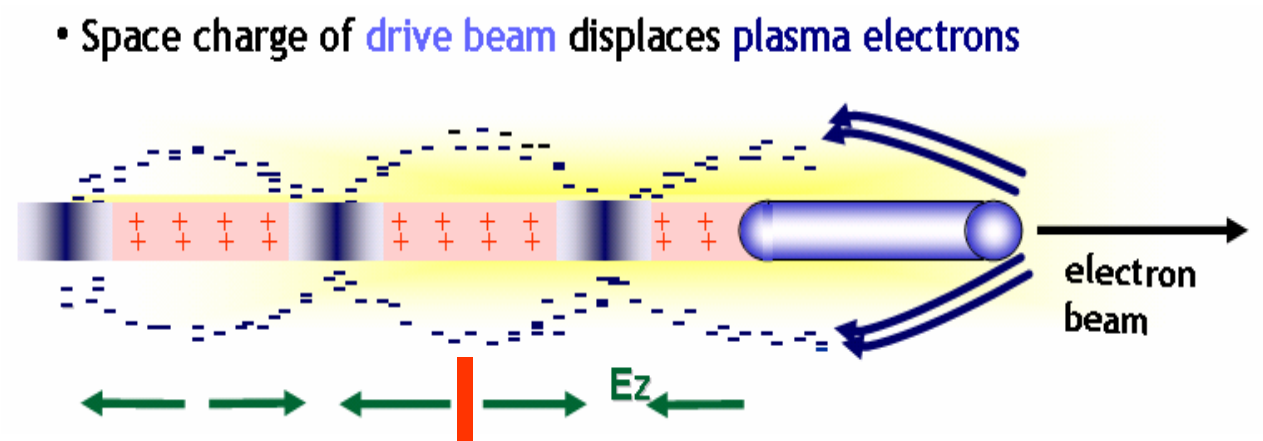
- Can we simulate it?

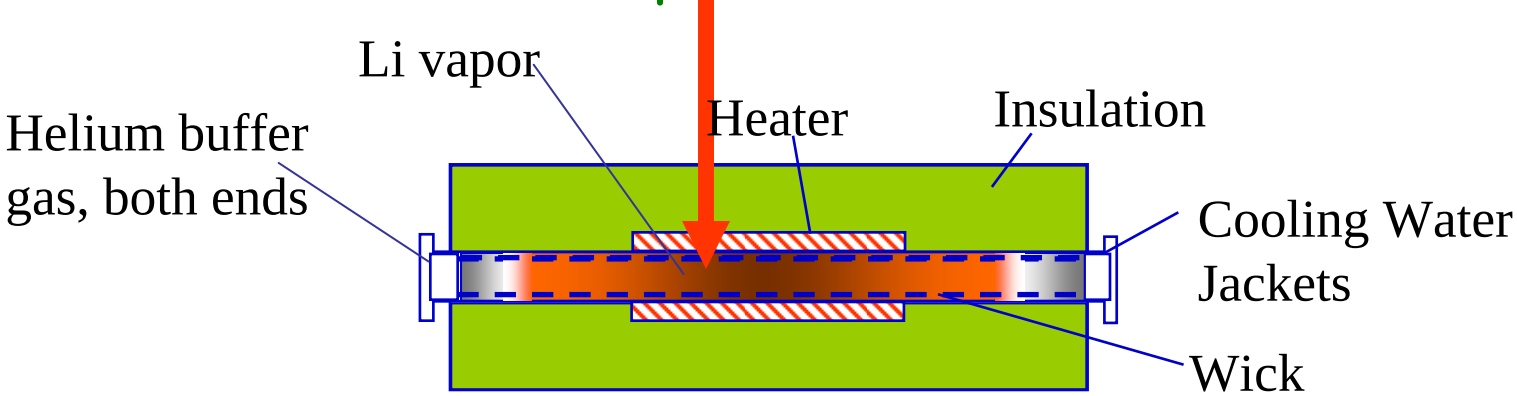
Particle Trapping in e-164X PWFA experiment
observed and controllable
by adjusting the longitudinal size of the drive bunch

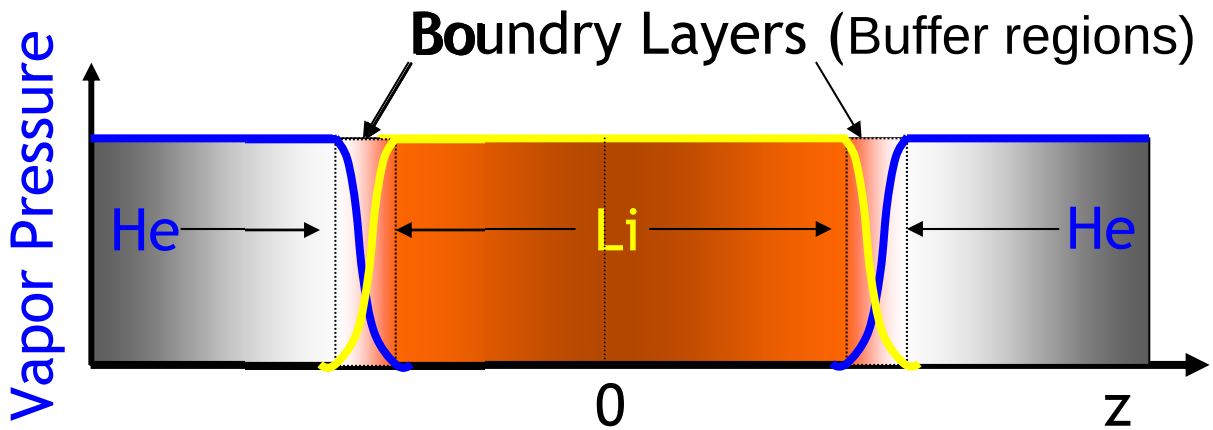
How do you do it?

Experimental Layout in FFTB

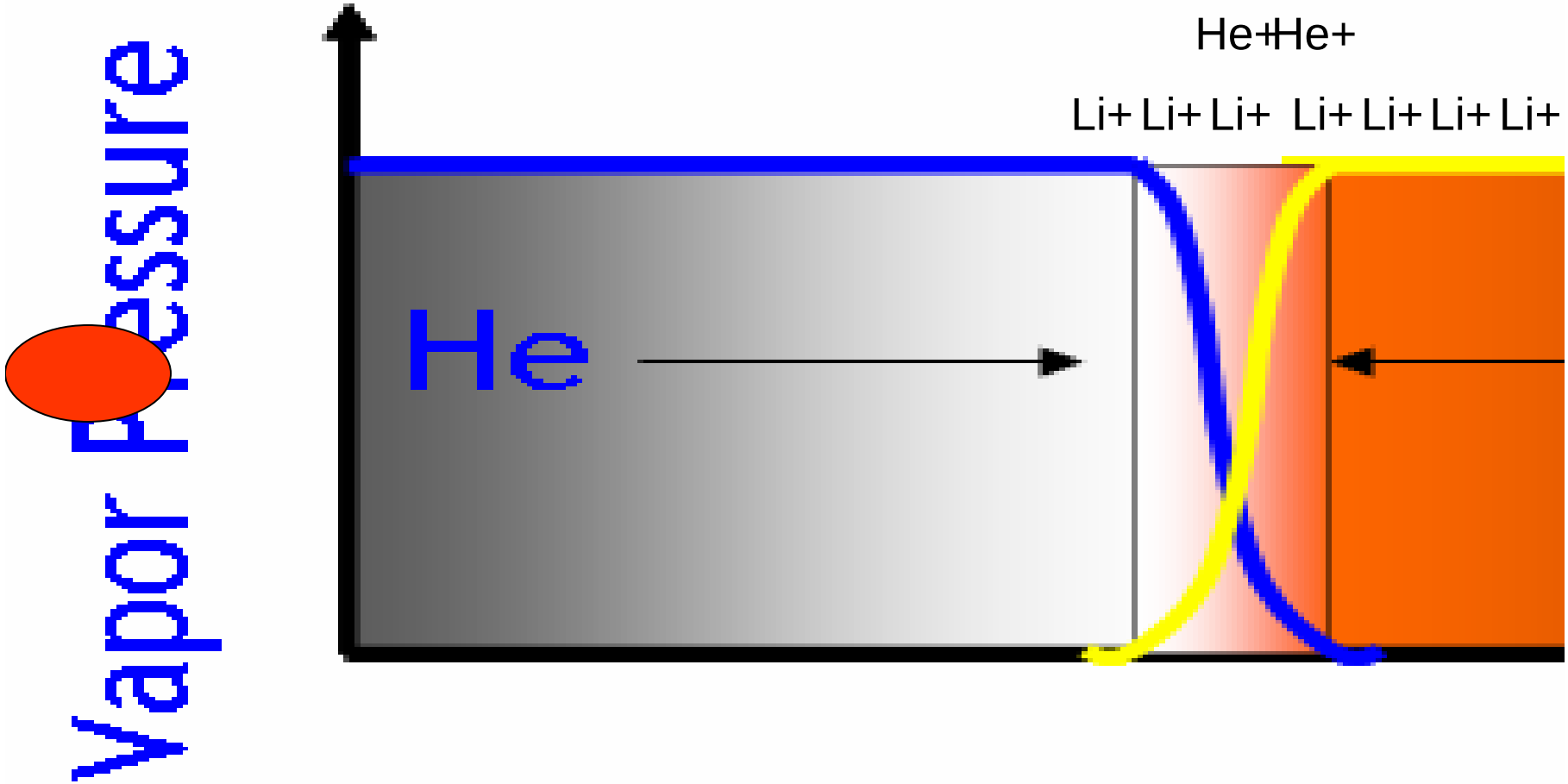



• Space charge of drive beam displaces plasma electrons
electron beam
Ez


Heat Pipe Oven
Li vapor
Helium buffer gas, both ends
Heater
Insulation
Cooling Water Jackets
Wick


Boundry Layers (Buffer regions)
Vapor Pressure
He
Li
He
0
z

heliumtrapall.mov

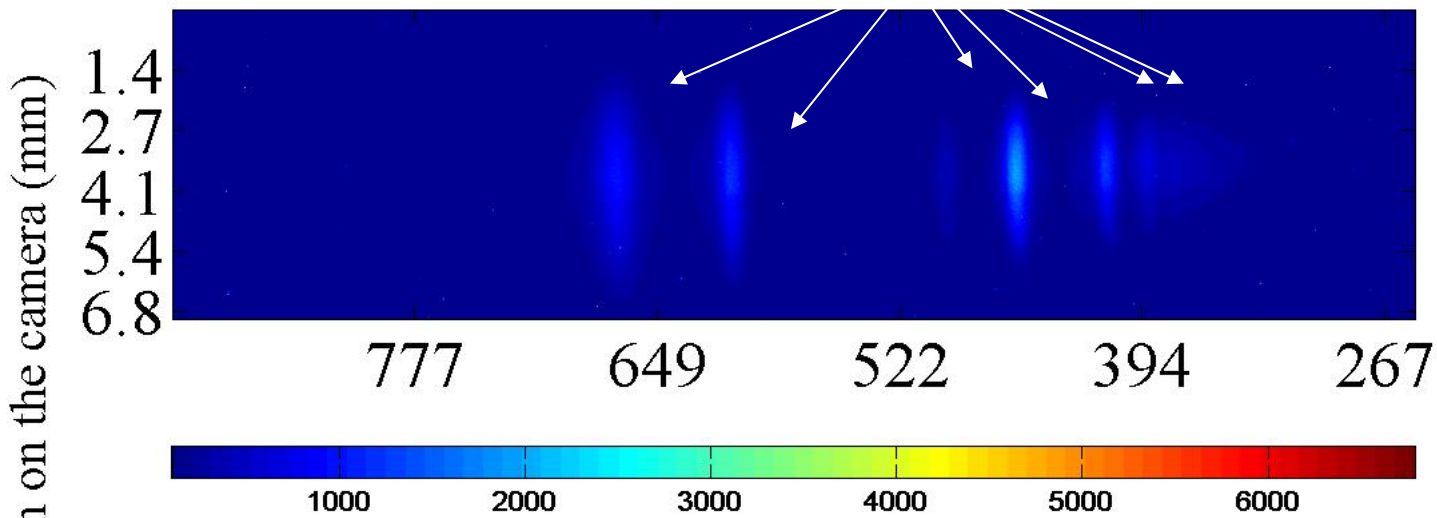


- Bunch does not ionize He I (24.5874 eV), but does ionize Li I (5.392 eV)
- Bunch is focused by the wake in the Li I plasma
- Bunch ionizes He I (24.5874 eV), but not Li II (75 eV)

LIGHT COLLECTION Reveals Evidence for Trapped Particles

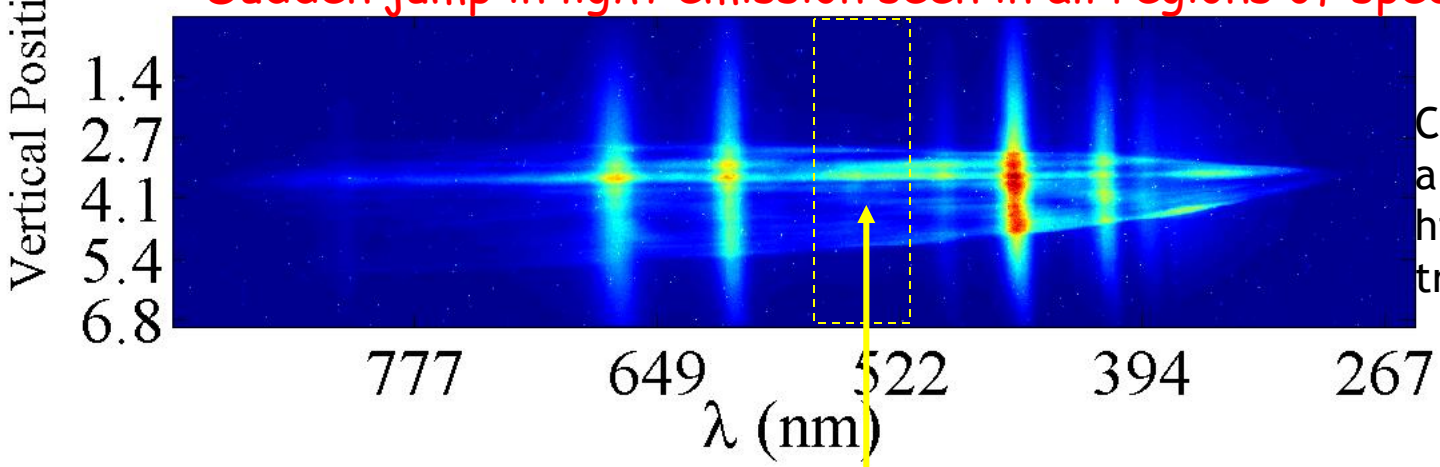
OTR and Cerenkov light by beam particles only is to weak to be visible

Line emission from wake heating



Corresponds to
a longer bunch,
lower wake amplitude,
no trapping

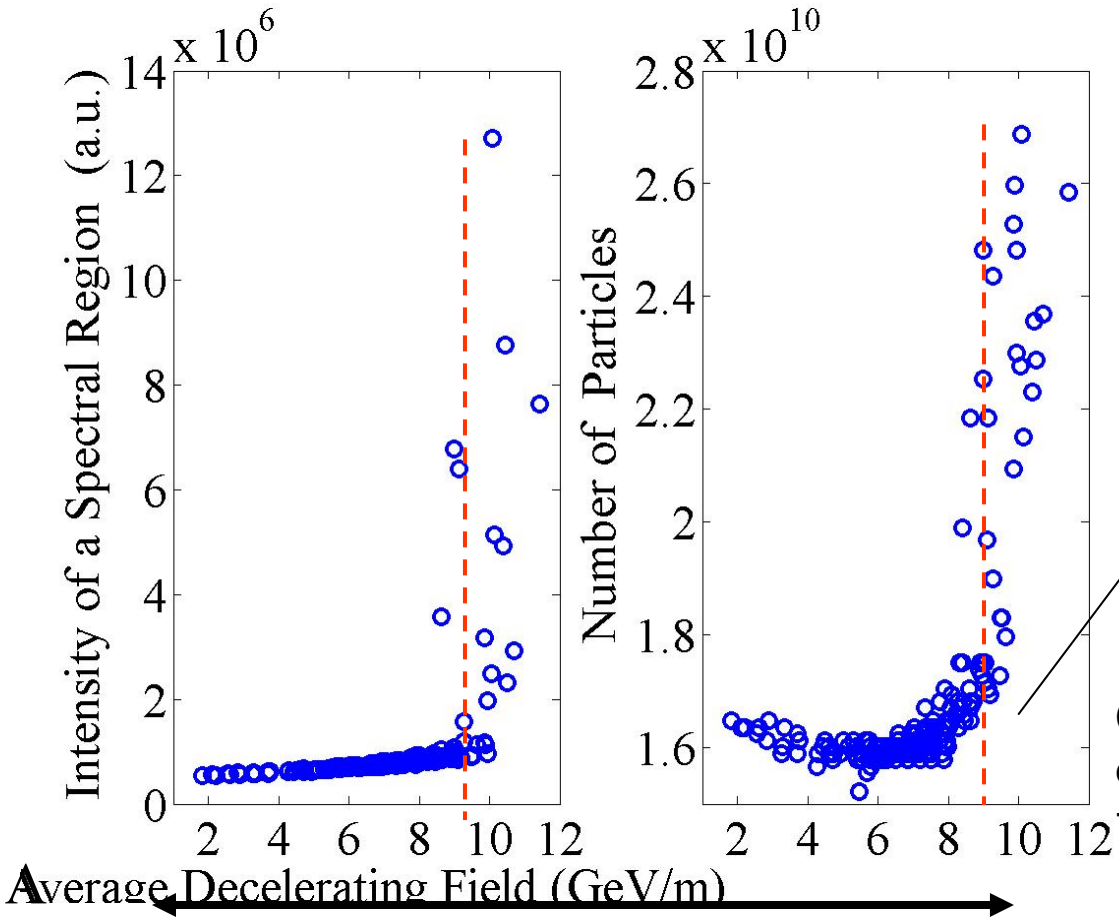
Sudden jump in light emission seen in all regions of spectrum



Corresponds to
a shorter bunch,
higher wake amplitude,
trapping

Continuum OTR and Cerenkov Light From Trapped Particles

Evidence For a Trapping Threshold



Number of particles measured by a fast current transformer located after the plasma

Clear threshold at ~9 GeV/m

Calculated by measuring energy change of the beam with the imaging spectrometer

Electron beam bunch length is being varied by means of changing the energy chirp of the beam through combination of bends and a chicane in the LINAC

Amount of light increases more than increase in charge

Indicating a coherent mechanism

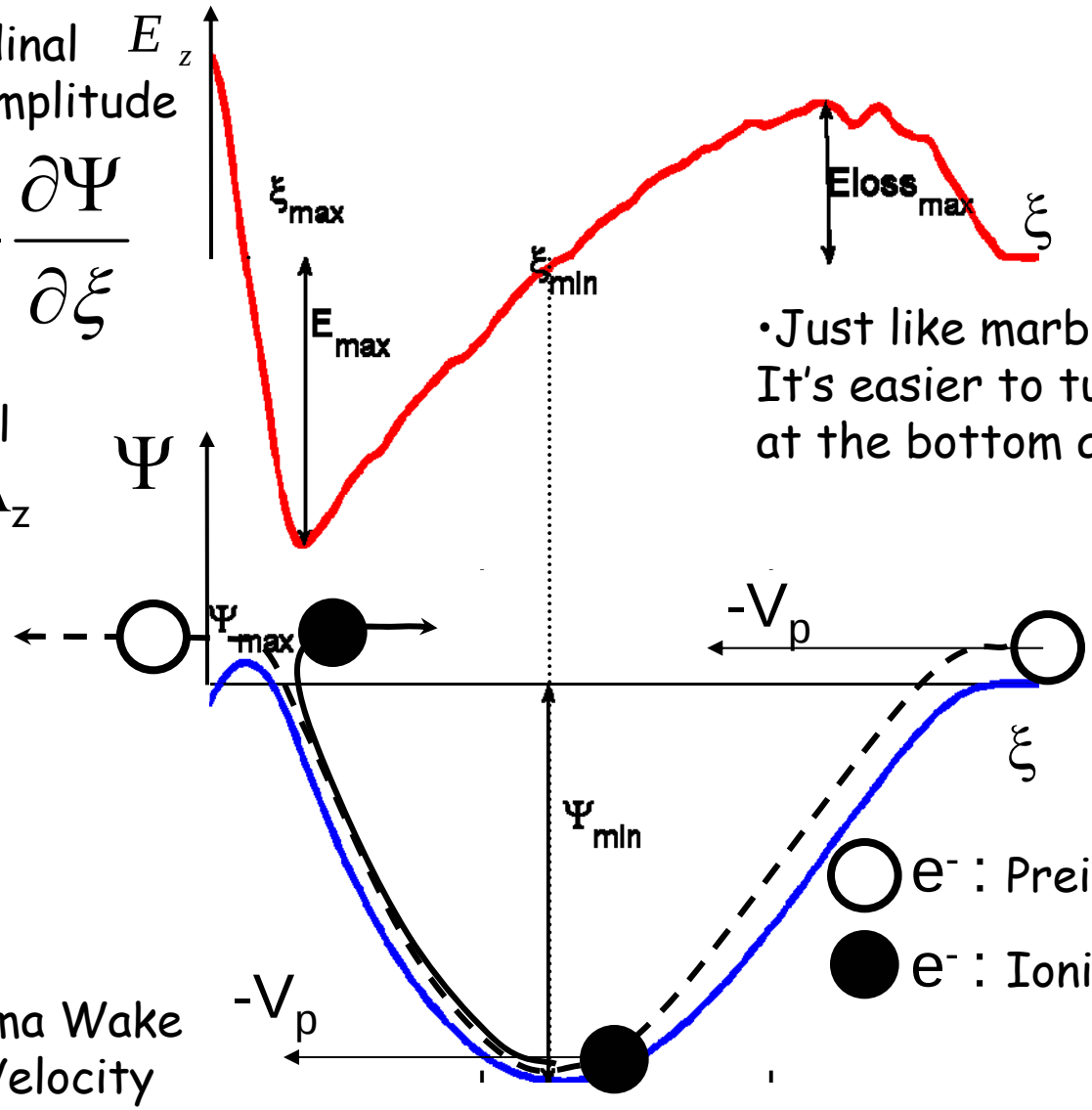
Cartoon of Trapping

Longitudinal Wake Amplitude

$$E_z = -\frac{\partial \Psi}{\partial \xi}$$

Potential

$\Psi = \Phi - A_z$



$$\xi = z - ct$$

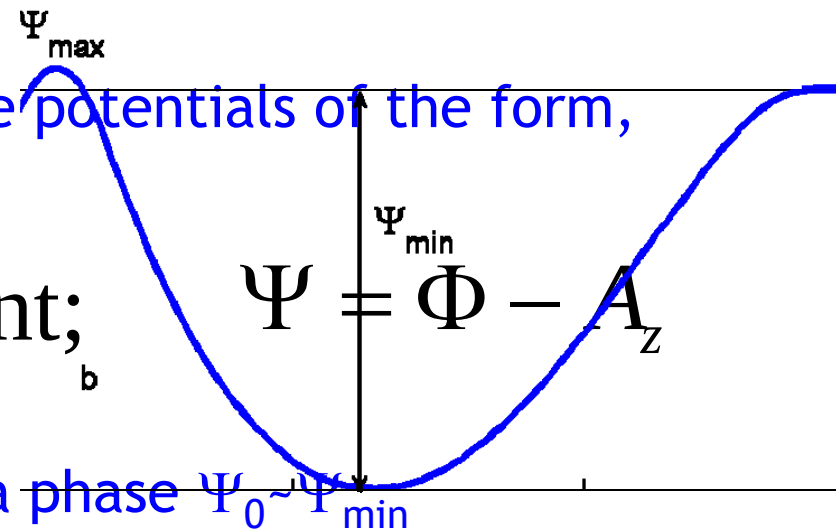
- Just like marbles rolling over a hill, It's easier to turn the marble starting at the bottom around

○ e^- : Preionized

● e^- : Ionized inside the wake

V_p: Plasma Wake Phase Velocity

Analytical Model of Trapping



Constant of motion for arbitrary wave potentials of the form,
A= A(zct), $\Phi=\Phi(z-ct)$

$$\gamma mc - P_z + q\frac{\Psi}{c} = \text{constant}; \qquad \Psi = \Phi - A_z$$

For Particles Born at Rest on Axis at a phase $\Psi_0 \sim \Psi_{min}$

$$\gamma mc + q\frac{\Psi_{min}}{c} = \text{constant}$$

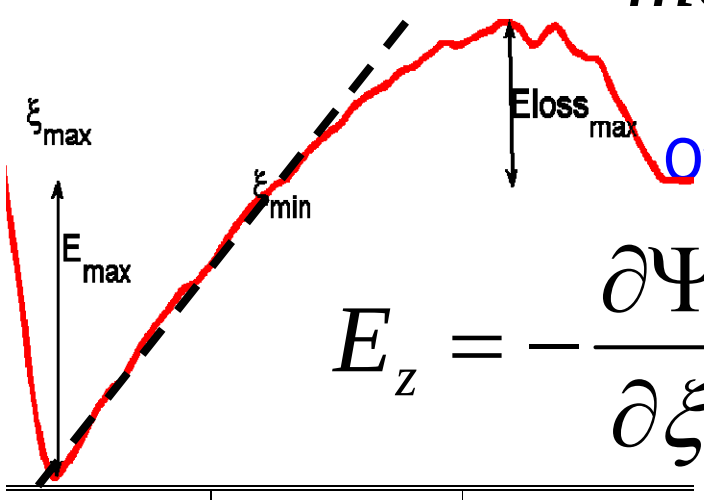
The trapping condition for these particles:

$$mc - \gamma mc + \gamma m V_p \le \frac{q}{c}(\Psi_{max} - \Psi_{min})$$

Making Use of The Linear Region of Wake

$$1-\frac{V_p}{c}\approx\frac{1}{2\gamma_p{}^2}<<\frac{1}{\gamma}\ \ \&\ \gamma\approx\gamma_p$$

$$mc^2\le q(\Psi_{\max}-\Psi_{\min})$$



Over the linear region

$$E_z=-\frac{\partial\Psi}{\partial\xi}\qquad E_z=k(\xi-\xi_{\min})$$

$$(\Psi_{\max}-\Psi_{\min})=E_{\max}(\xi_{\min}-\xi_p)/2$$

The Analytic Expression For The Threshold

$$mc^2 \le q(\Psi_{max} - \Psi_{min}) \longrightarrow E_{max} \ge \sqrt{\frac{2kmc^2}{e}}$$

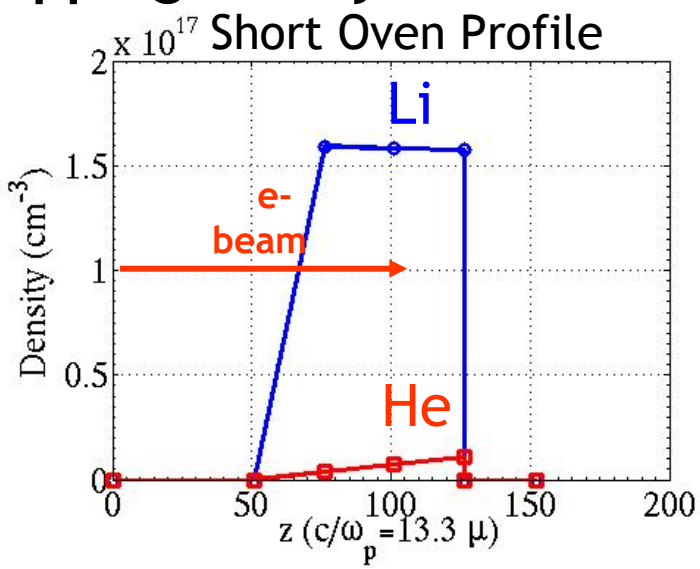
When Normalized to Simulation Units

$$E' = \frac{e}{mc\omega_p} E; k' = \frac{e}{m\omega_p^2} k$$

$$E_{max} \ge \sqrt{2k'}$$

Short simulations to test trapping theory

Simulation Parameters: the same as the full e164X run except spot size is 2.4 μ to mock focusing of the beam and beam is propagated only a short portion of the buffer region

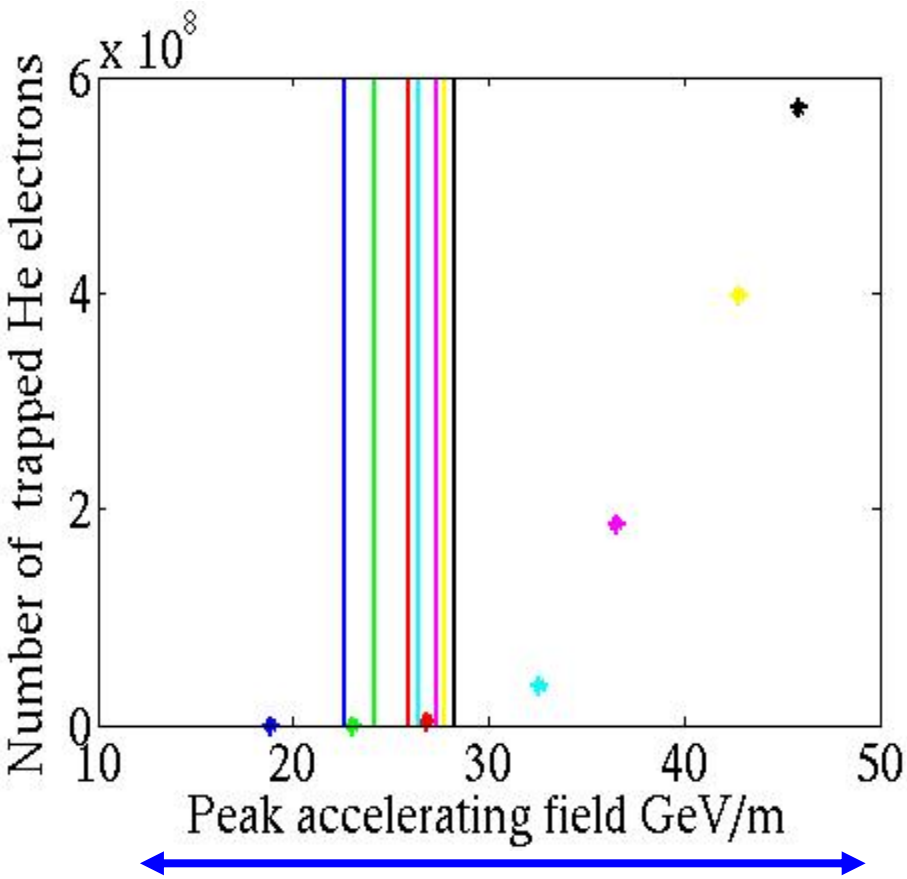


Osiris Simulations Show Clear Threshold and Verifies Theory

Vertical Lines are the analytic estimates each corresponds to a different simulaton

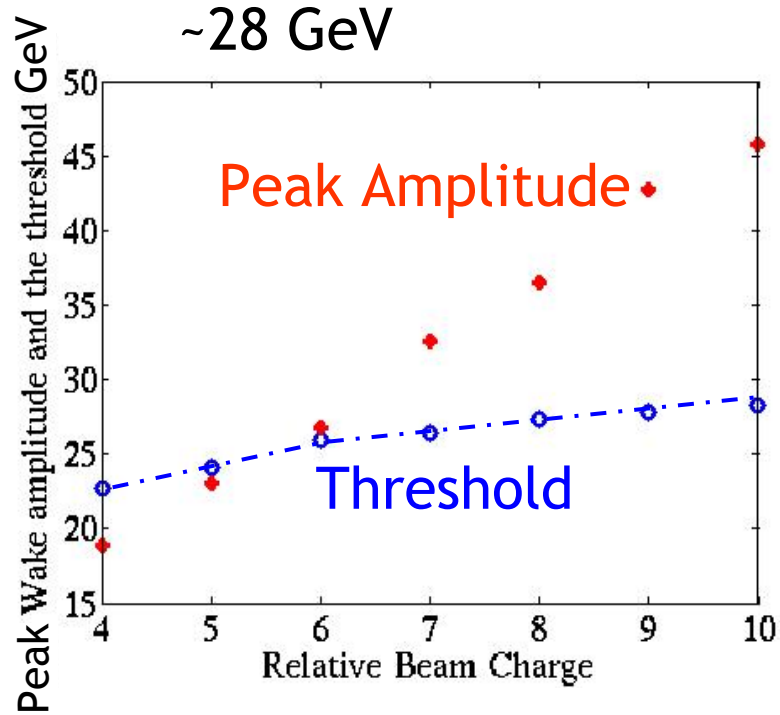
k' : calculated from linear fits to E_z from simulations

Peak Field : calculated from simulations

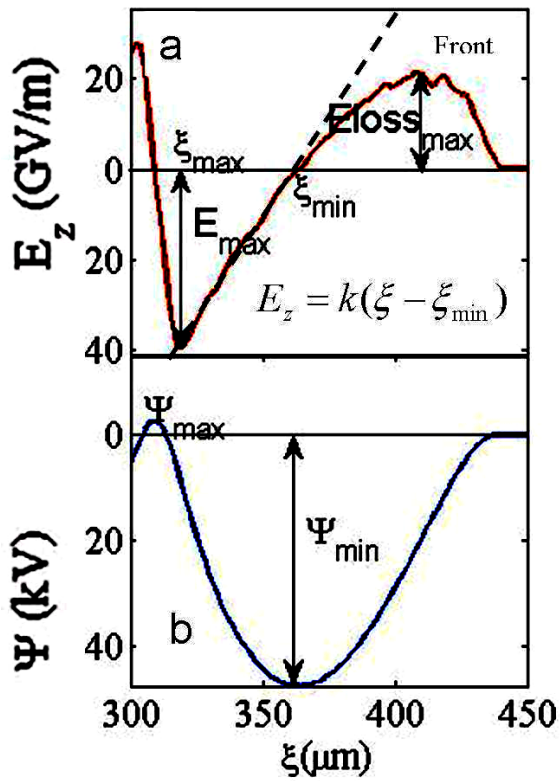


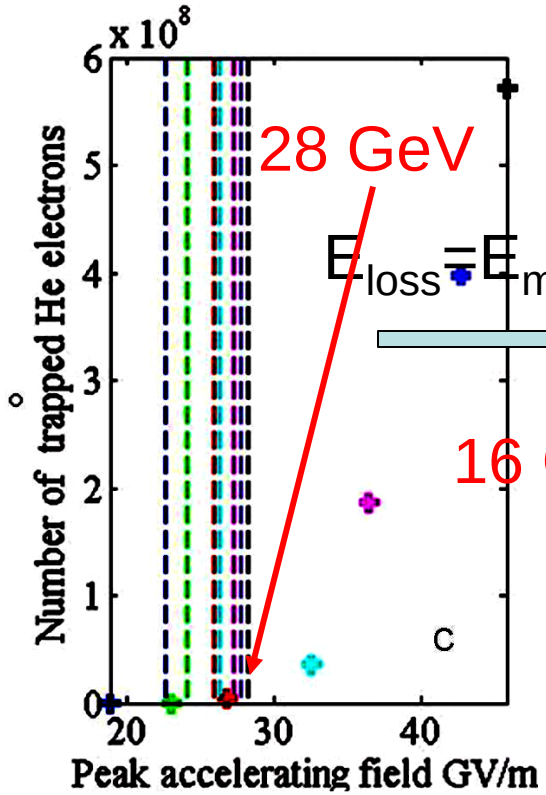
Beam charge is varied from 0.4 to 1 times that of original beam from left to right

Simulation threshold at ~28 GeV

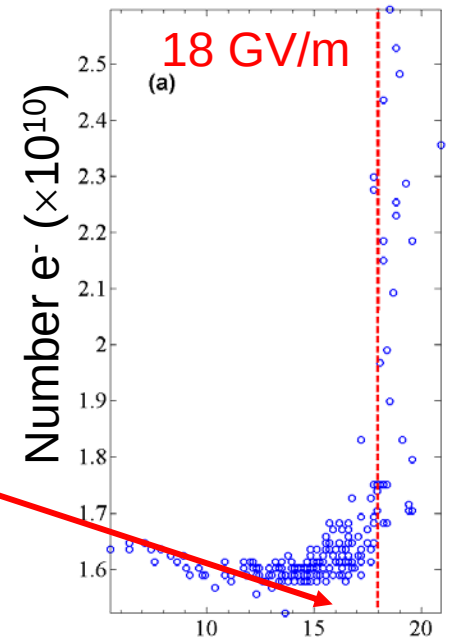


THRESHOLDS COMPARISON





Experiment



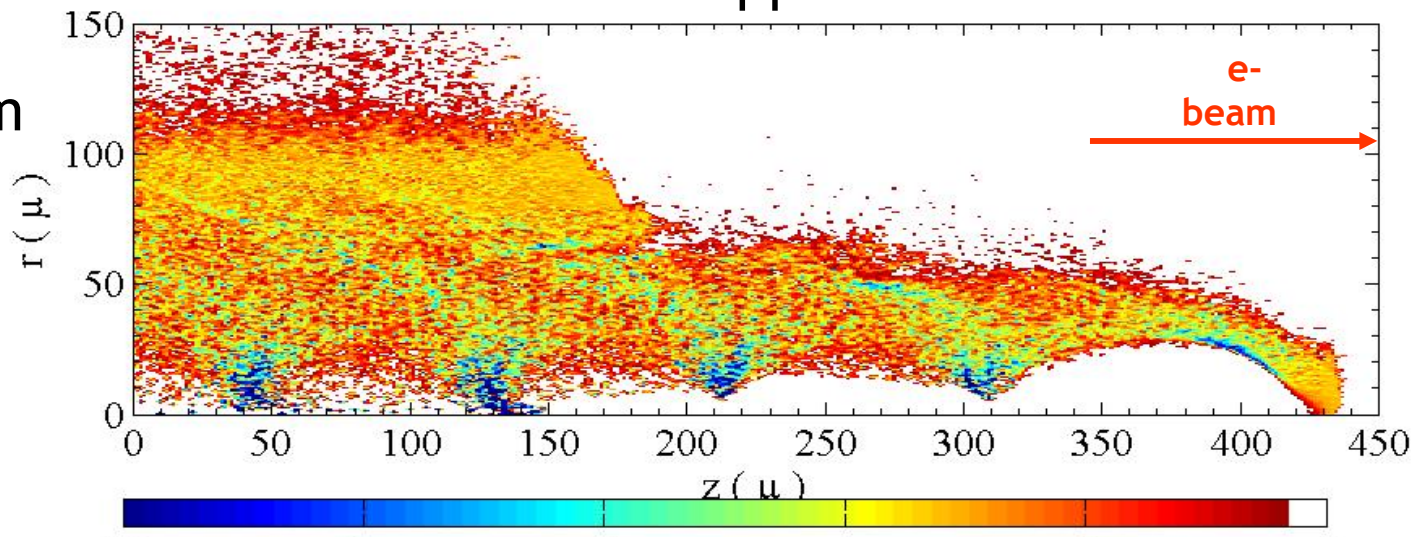
Peak Decellerating Field (GV/m)

➡ Excellent "analytical model" - simulations - experiment agreement!!!

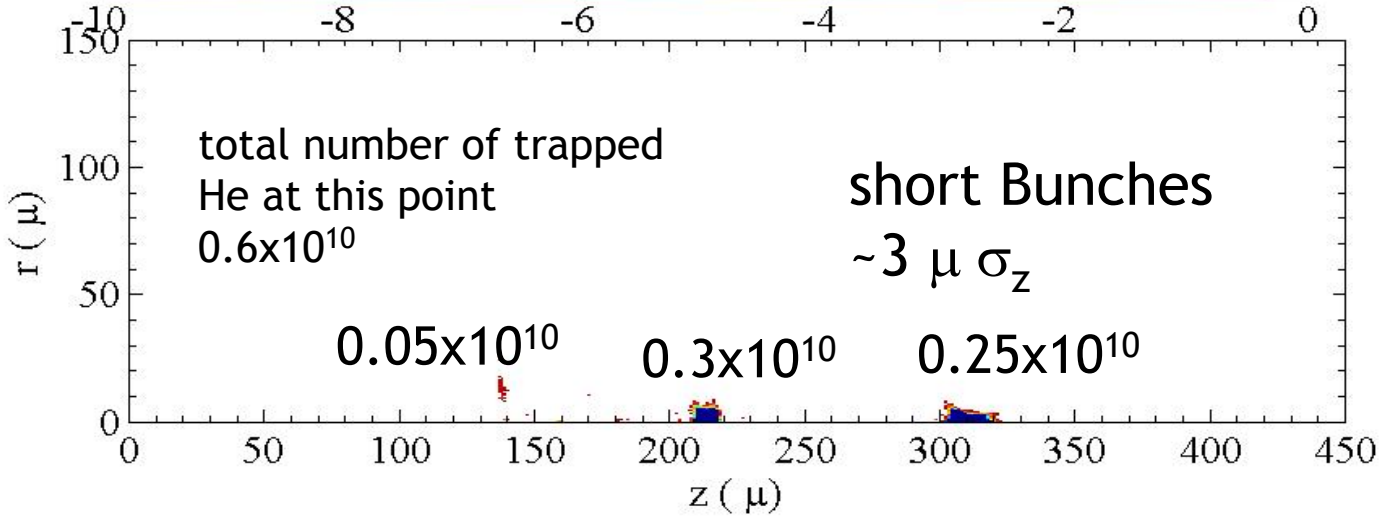
OSIRIS Simulation: Real Space (r-z) Of Li & He Electrons

Lithium electrons support the wake

Li at z=11.3 cm



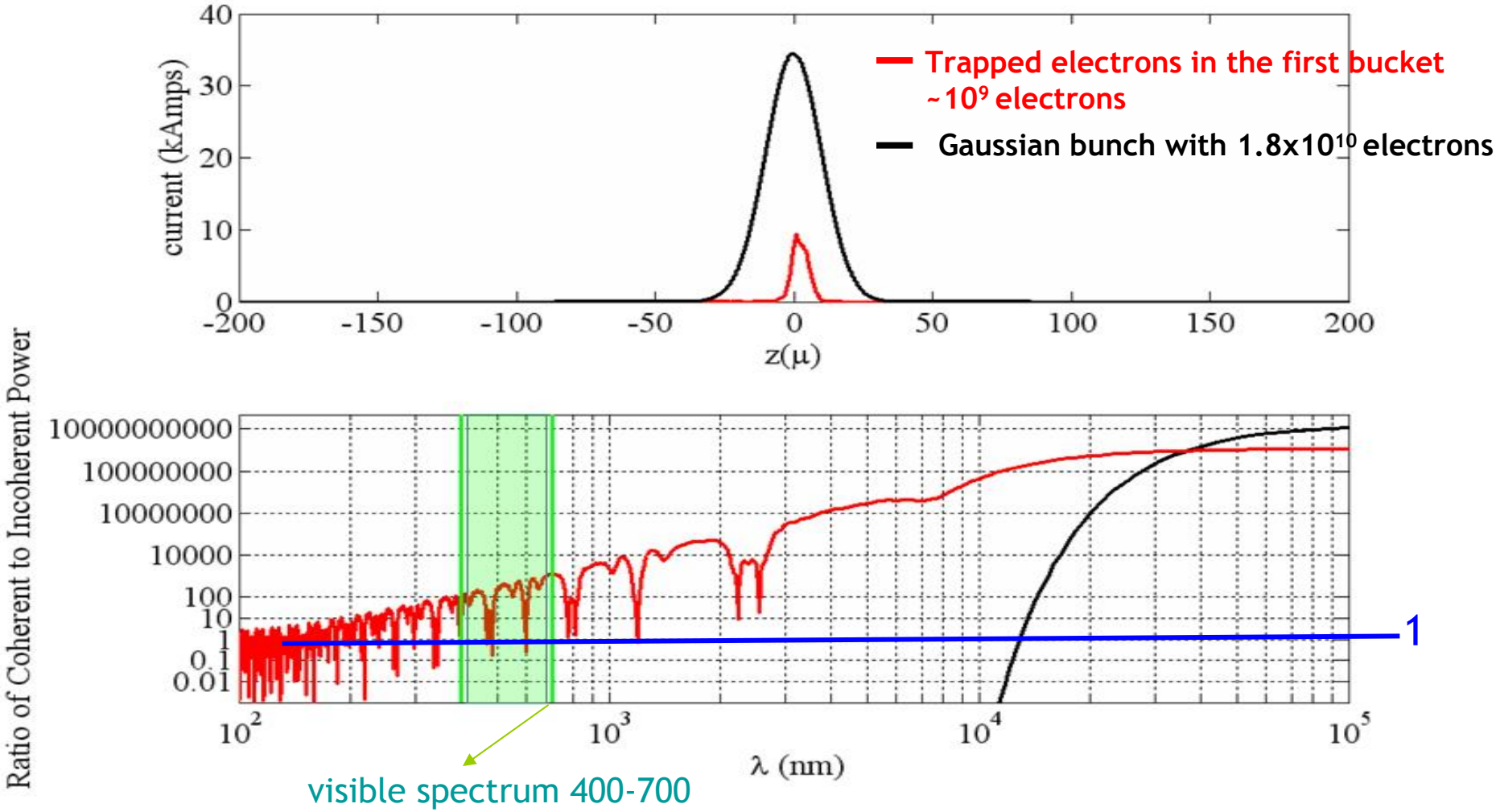
He at z=11.3 cm



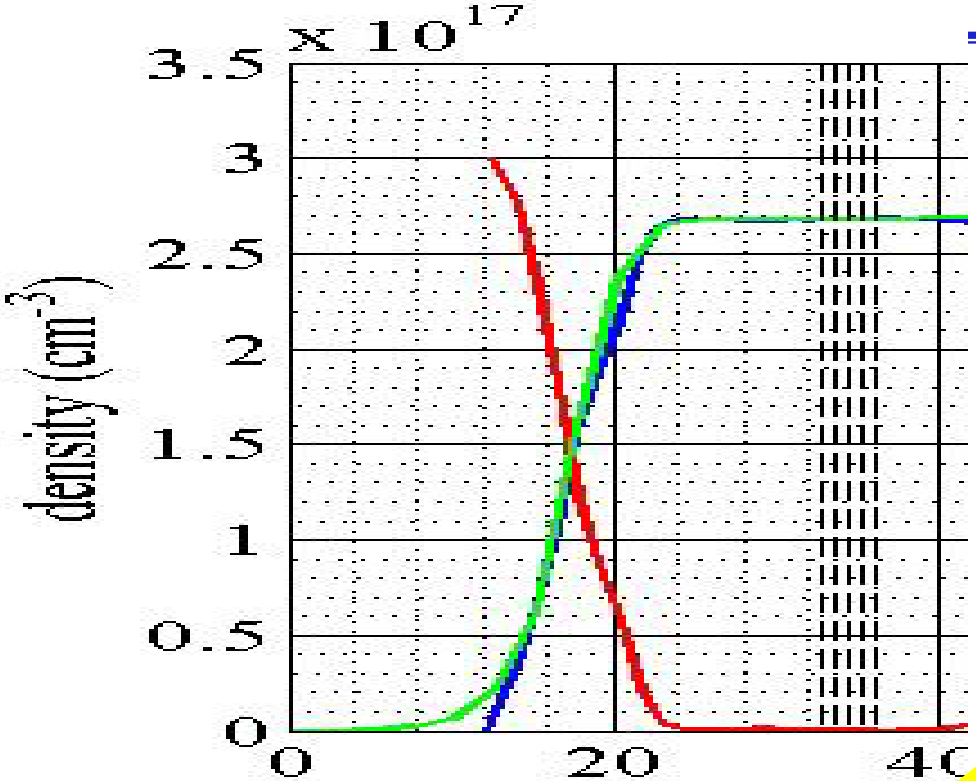
He electrons trapped inside the wake

COHERENT RADIATION BUNCH LENGTH THRESHOLD

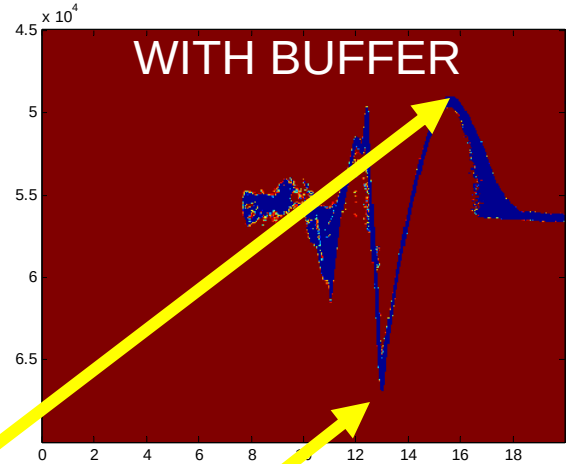
Non-Gaussian trapped bunches can account for emission of Coherent Continuous Radiation

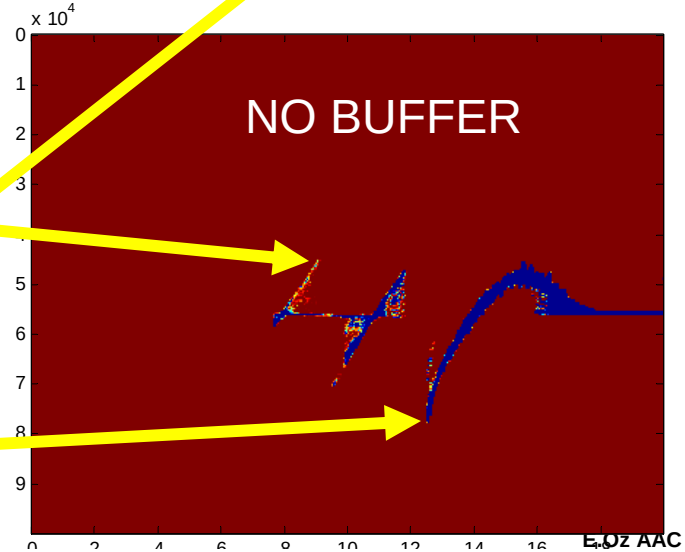


COMPARING EFFECT OF TRAPPED ELECTRONS ON MAX ENEGRY GAIN AND LOSS



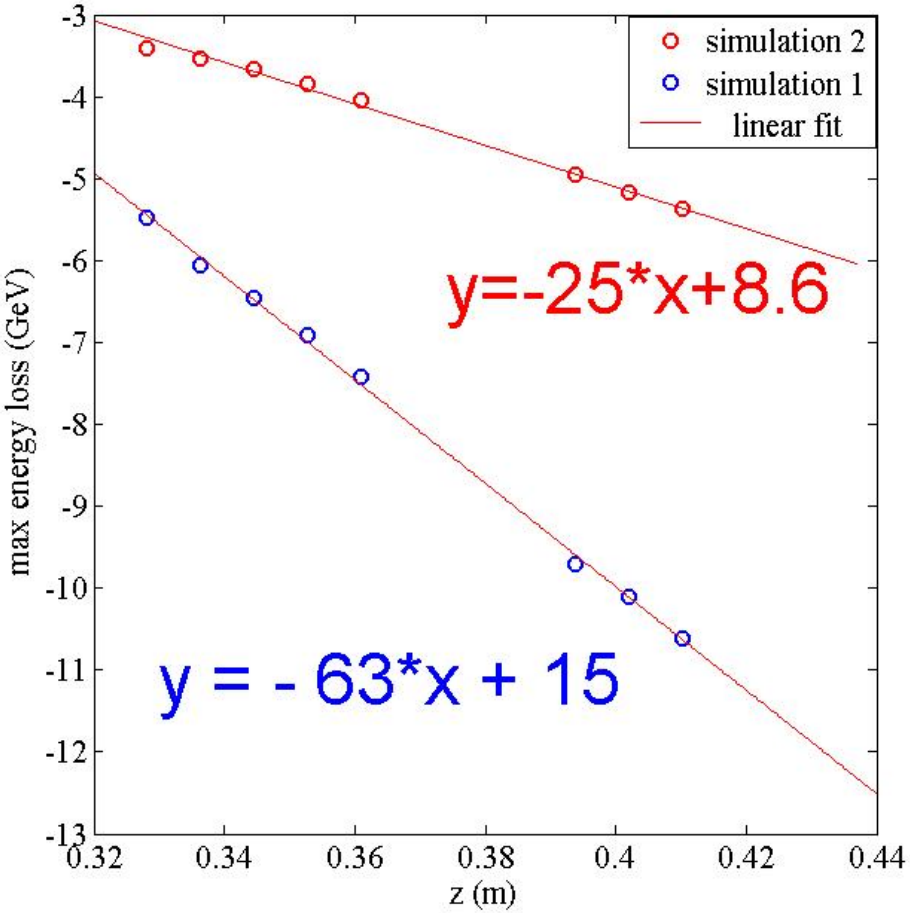
•Dashed lines represent points of comparison

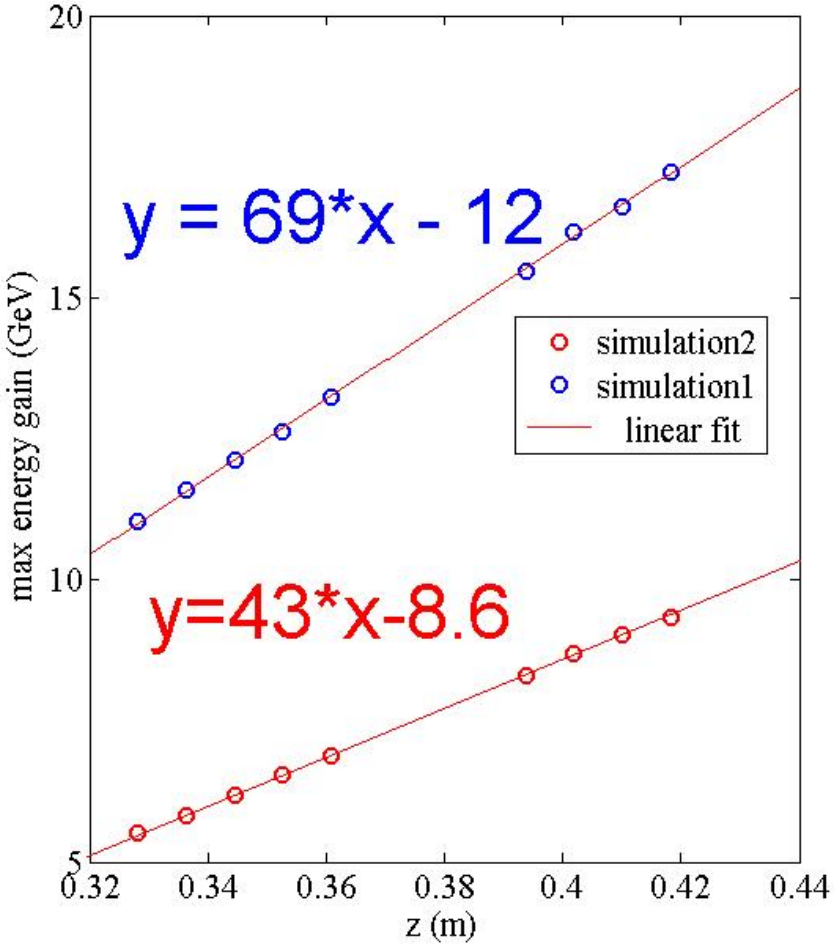




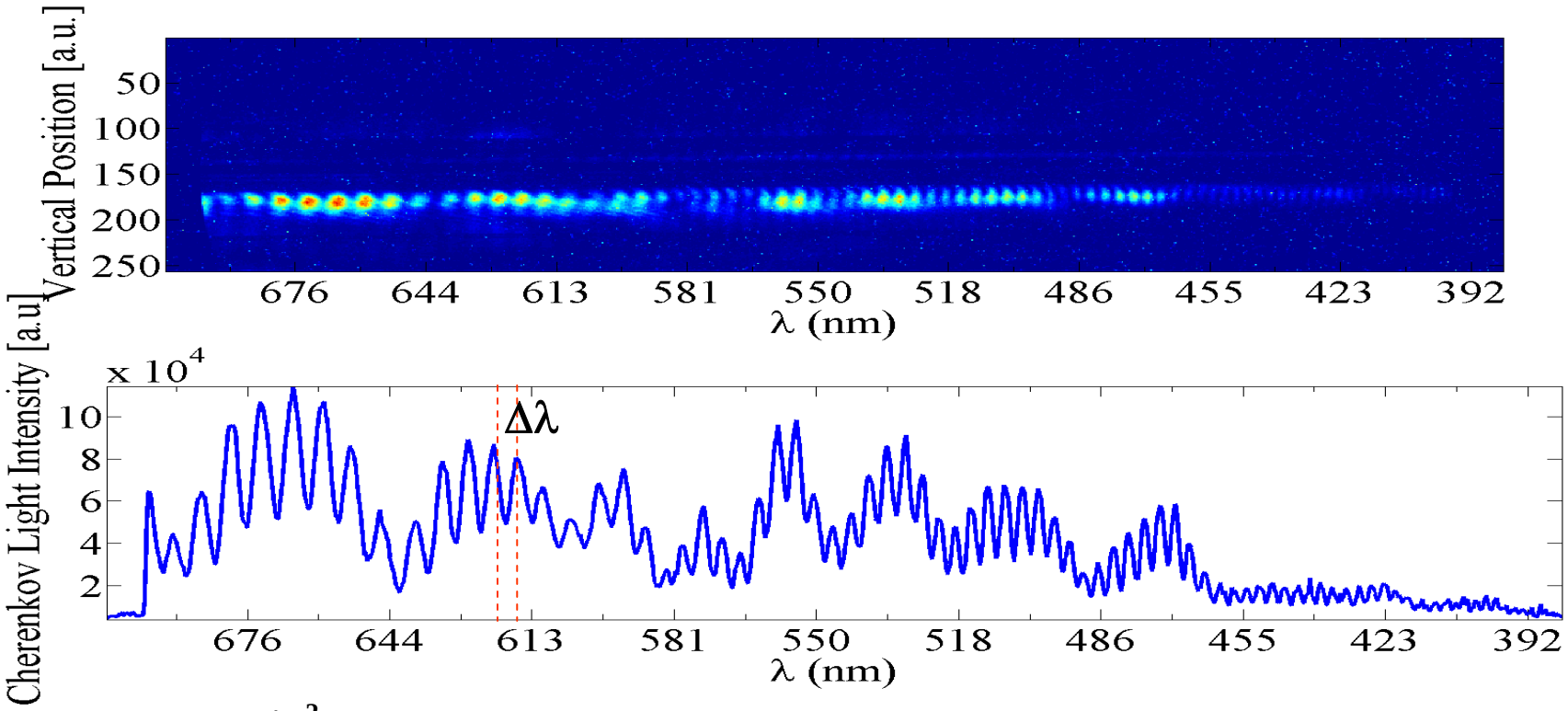
MAX LOSS

MAX GAIN


simulation 2
simulation 1
linear fit
y=-25*x+8.6
y = - 63*x + 15
max energy loss (GeV)
z (m)
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
0.32
0.34
0.36
0.38
0.4
0.42
0.44


y = 69*x - 12
simulation2
simulation1
linear fit
y=43*x-8.6
max energy gain (GeV)
z (m)
20
15
10
5
0.32
0.34
0.36
0.38
0.4
0.42
0.44

Plasma Wavelength
From trapped particle interference pattern



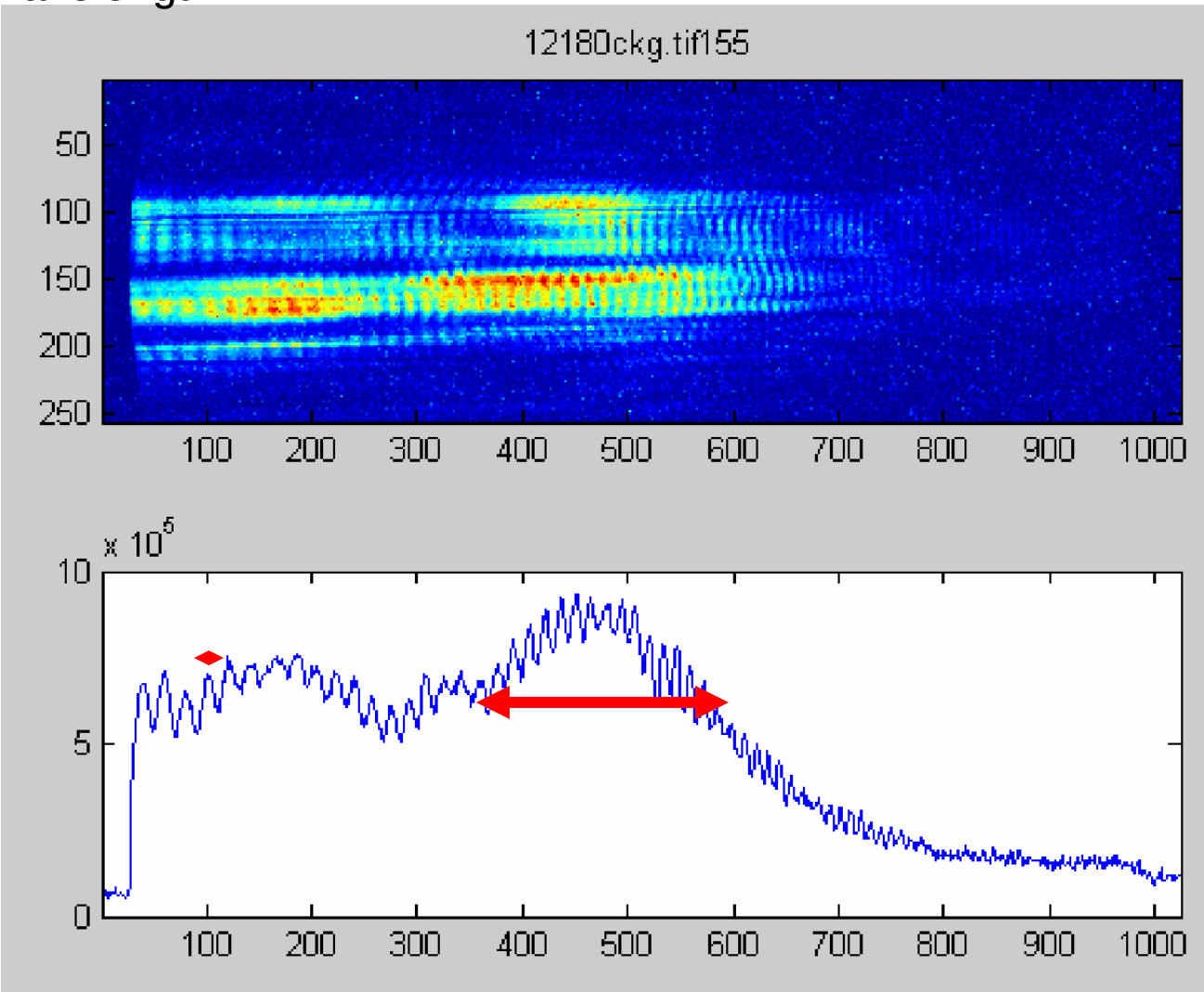
$$\Delta z = \frac{\lambda^2}{2\Delta\lambda}$$

Bunch Spacing = $\Delta z \approx 70\ \mu$,

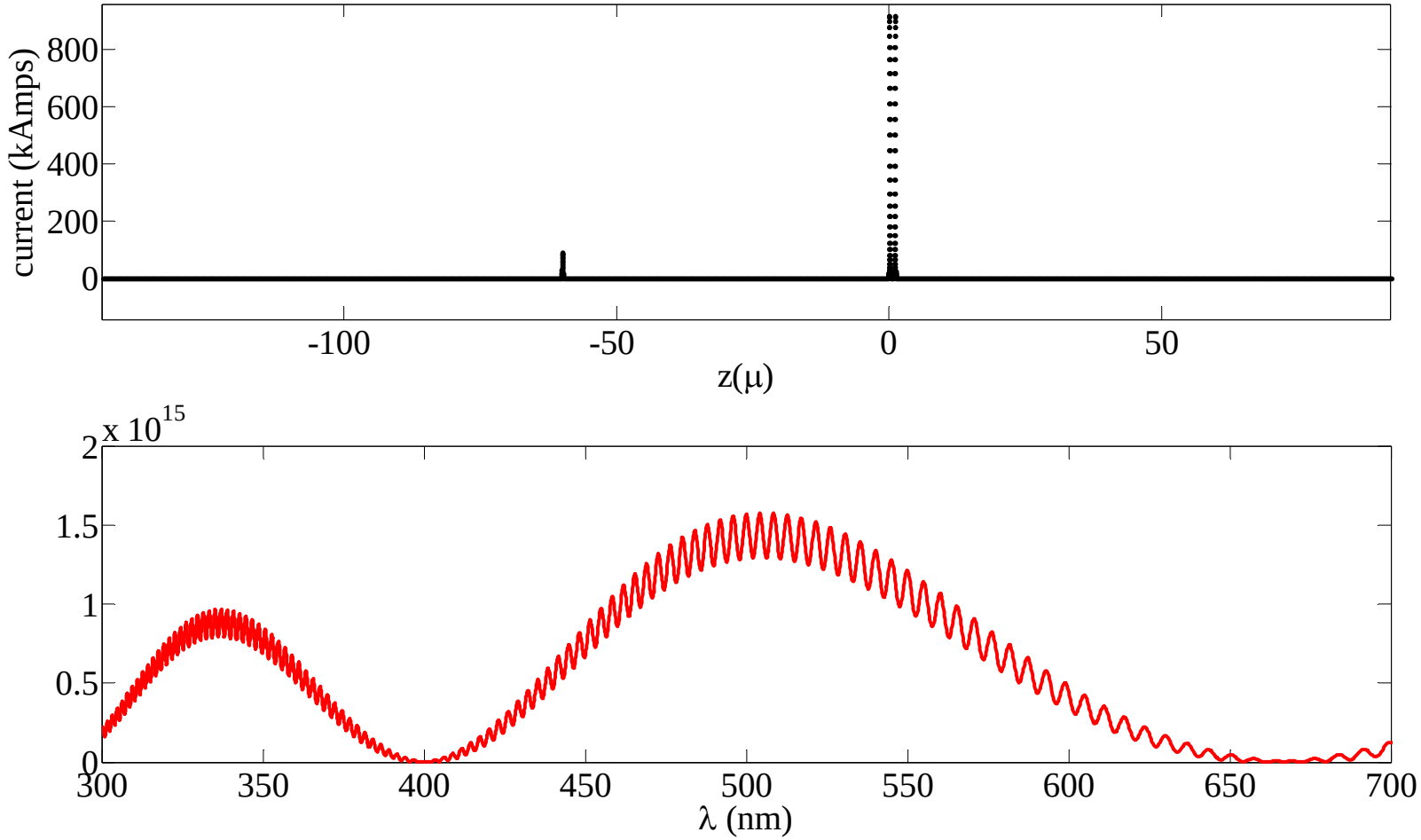
longer than linear plasma wavelength, $\lambda_p = 64\ \mu$.

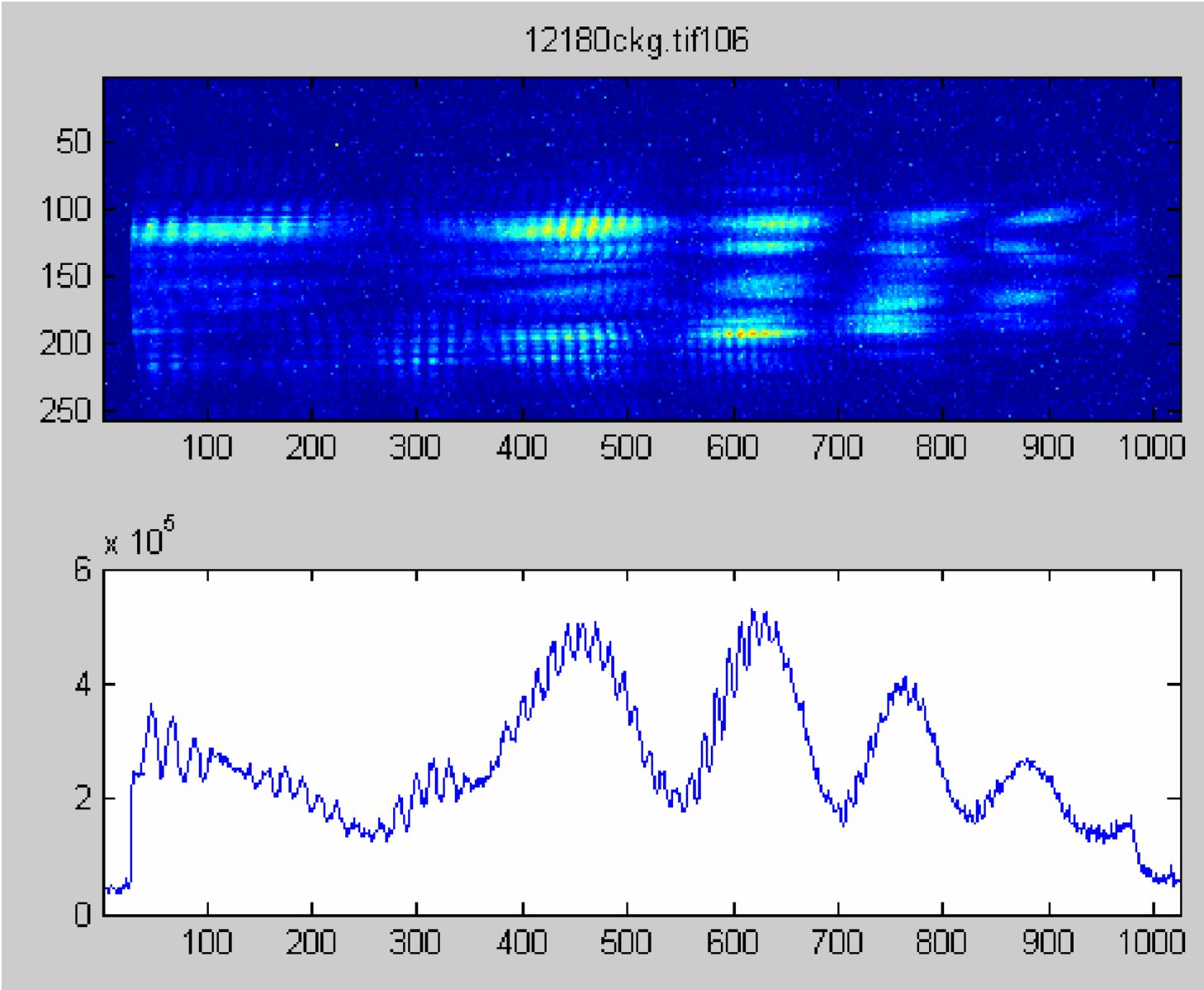
- Evidence for short bunches of trapped particles

Spectrograph image showing two modulations one with shorter and one with longer wavelength

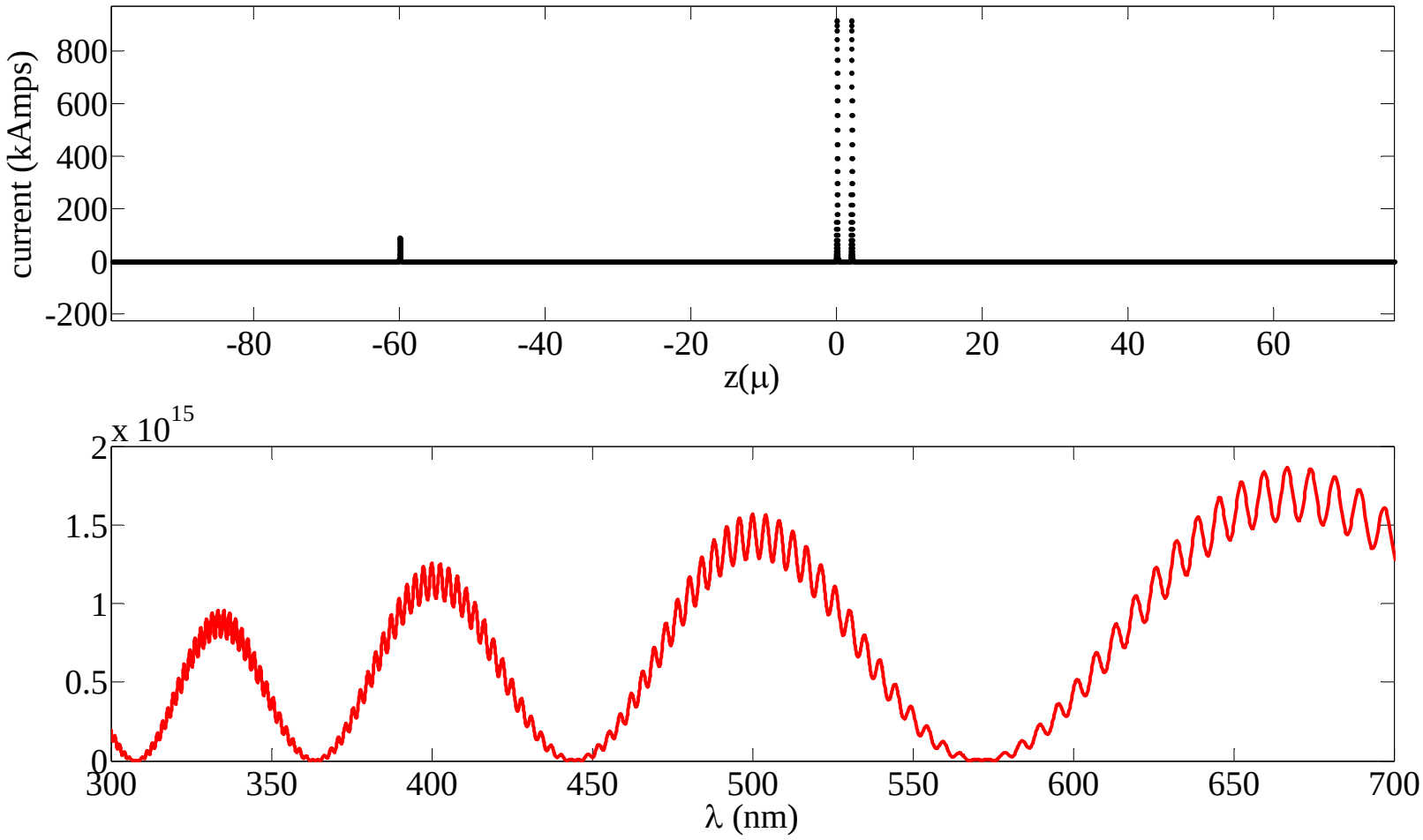


Fft of three Gaussians, 1micron separation
Each Gaussian has 500 nm sigz

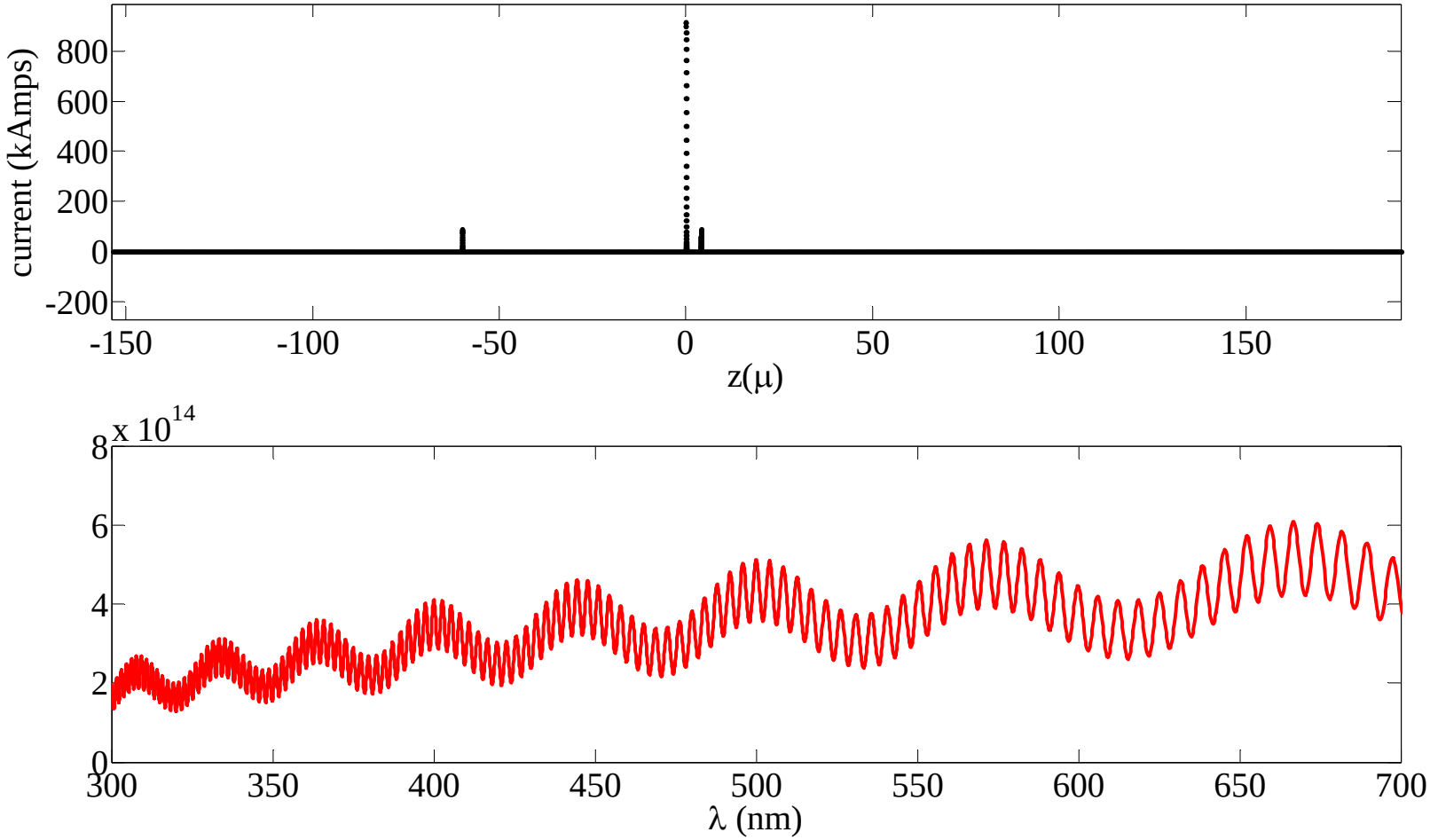


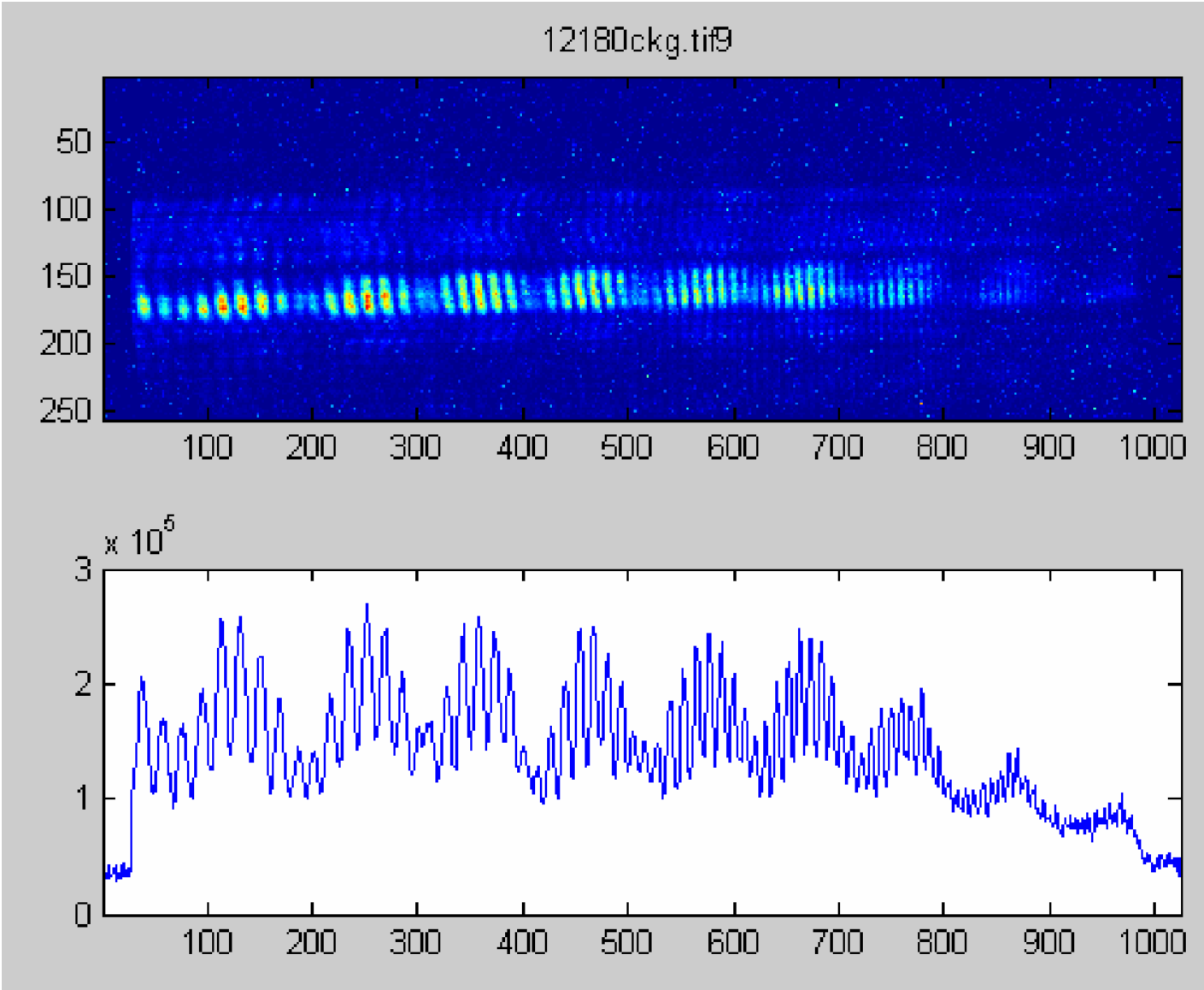

12180ckg.tif106
50
100
150
200
250
100
200
300
400
500
600
700
800
900
1000
x 10^5
6
4
2
0
100
200
300
400
500
600
700
800
900
1000

2 micron separation



4 micron separation




12180ckg.tif9
50
100
150
200
250
100
200
300
400
500
600
700
800
900
1000
x 10^5
3
2
1
0
100
200
300
400
500
600
700
800
900
1000

Conclusions

- First experimental measurement of well defined threshold

  - Theory for trapping threshold

$$E_{th} \approx \sqrt{2k'}; \; k' \rightarrow 0.5$$

For large amplitudes in nonlinear regime

$$E_{th} \approx \frac{mc\omega_p}{e}$$

Well known 1-d Dawson Wave Breaking limit.

- Trapped particles are result of self ionization, for the parameters we run This mostly occurred in Helium buffer but higher density beams required for Near future colliders do ionize multiple ions (Li++,Ar+++++++ etc) see Reza Gholizadeh's Talk on ion motion at these proceedings

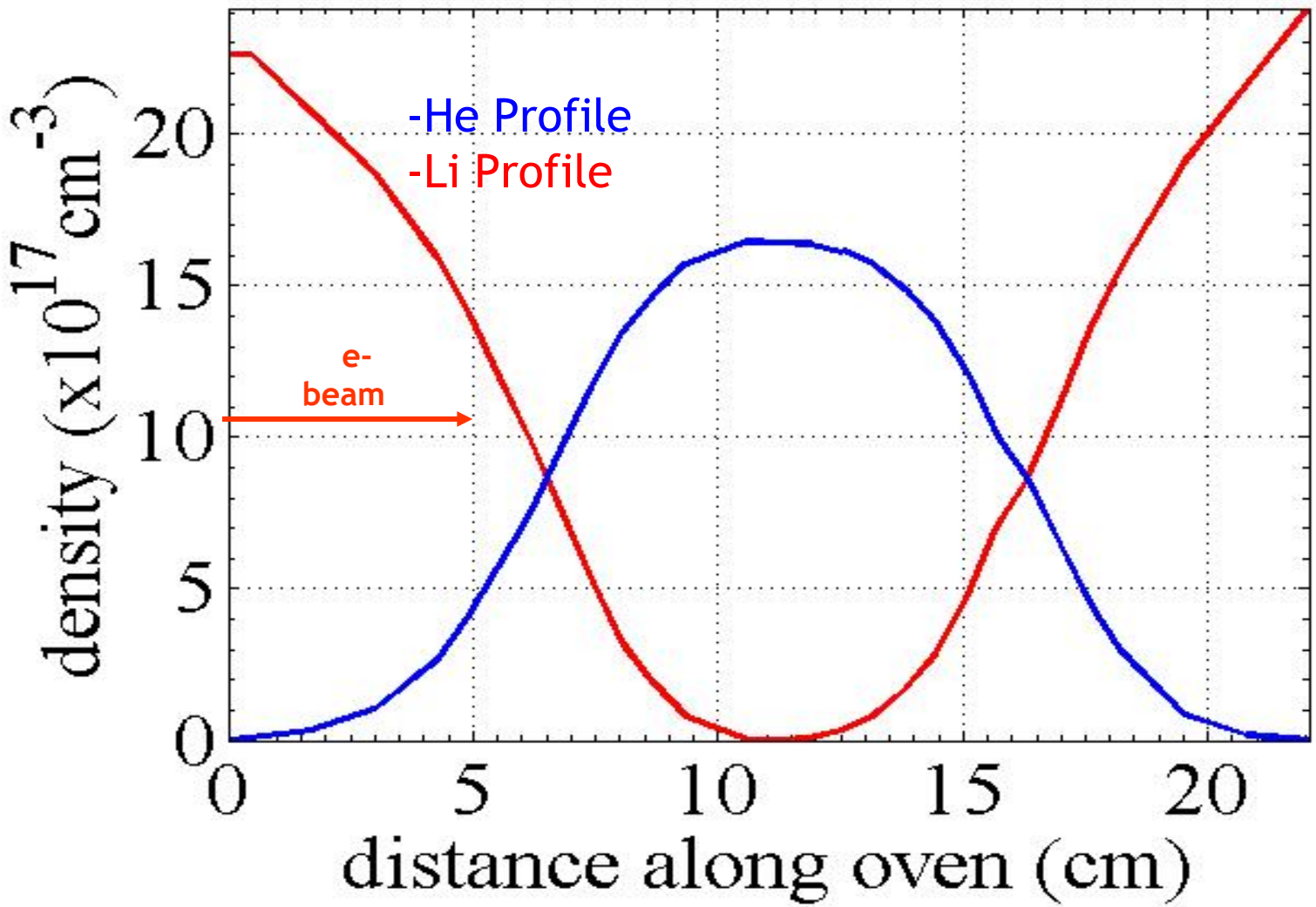
- Trapped particles are produced in multiple buckets, emit coherent visible radiation indicating extremely short structure

- Trapped particles reduce the accelerating wake considerably

- **Trapped particles are not really trapped they are freed! freed from the binding forces of the nucleus to surf the wakes of the future.**

THANK YOU FOR LISTENING!

Simulation of the Experiment with OSIRIS*



*2-D Object Oriented Fully Parallel PIC (Particle In Cell) Code

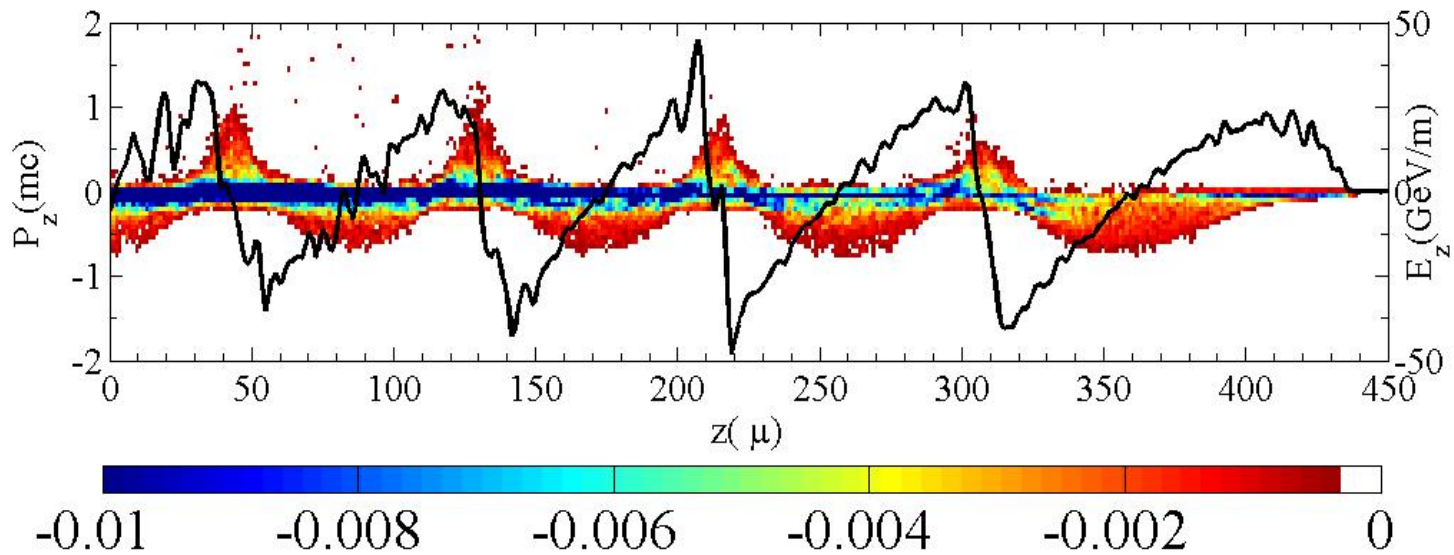
Parameters of OSIRIS Simulation For The Full E-164X PWFA Experiment

Beam Spot Size (σ_r) Gaussian	12 μ
Beam FWHM (non-Gaussian longitudinal distribution)	70 μ
Beam Energy	28.5 GeV
Number of Beam e^-	1.88×10^{10}
Li Gas Density (n_0)	1.6×10^{17} cm^{-3}
Number of Simulation Cells	500 x 600 moving
Beam Particles/cell	25
Gas Particles/cell	1
dt ($1/\omega_p$)	0.0286
Cell Size $\Delta z \times \Delta r$	0.09×0.04 c/ω_p

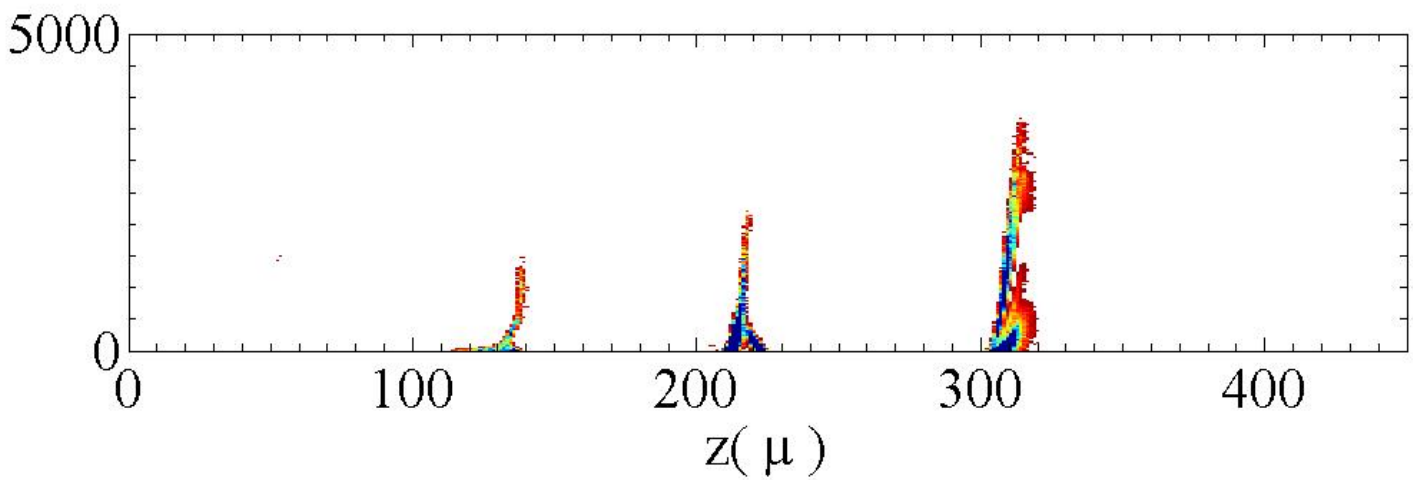
OSIRIS Simulation:
Phase Space (P_z-z) Of Li & He Electrons and the on-axis line out of the E_z

Li electrons do not get trapped

Li at z=11.3 cm



He at z=13.4 cm

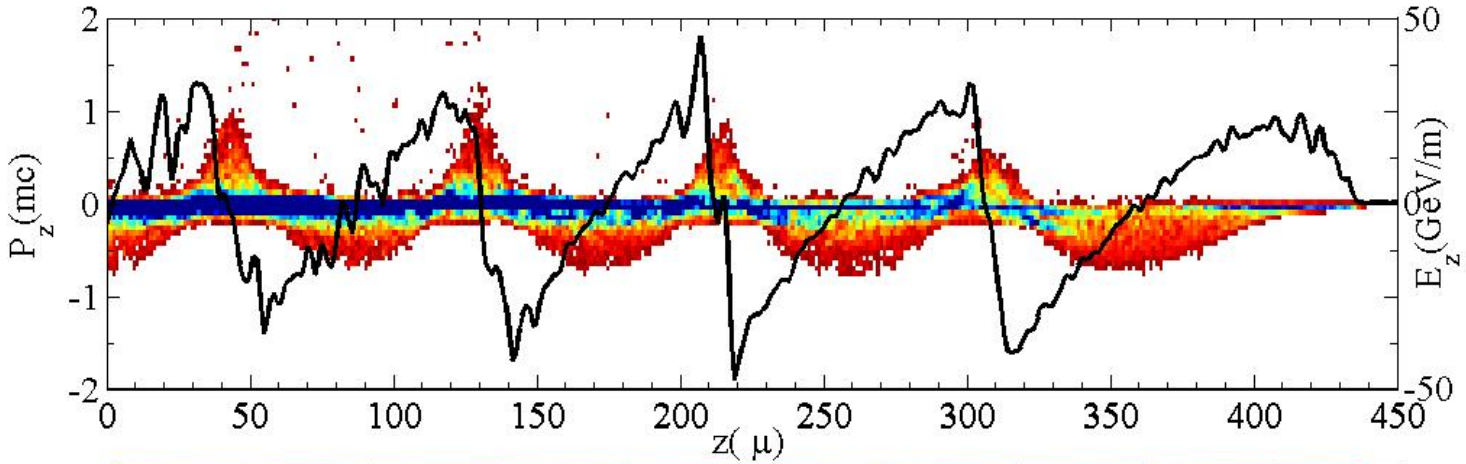


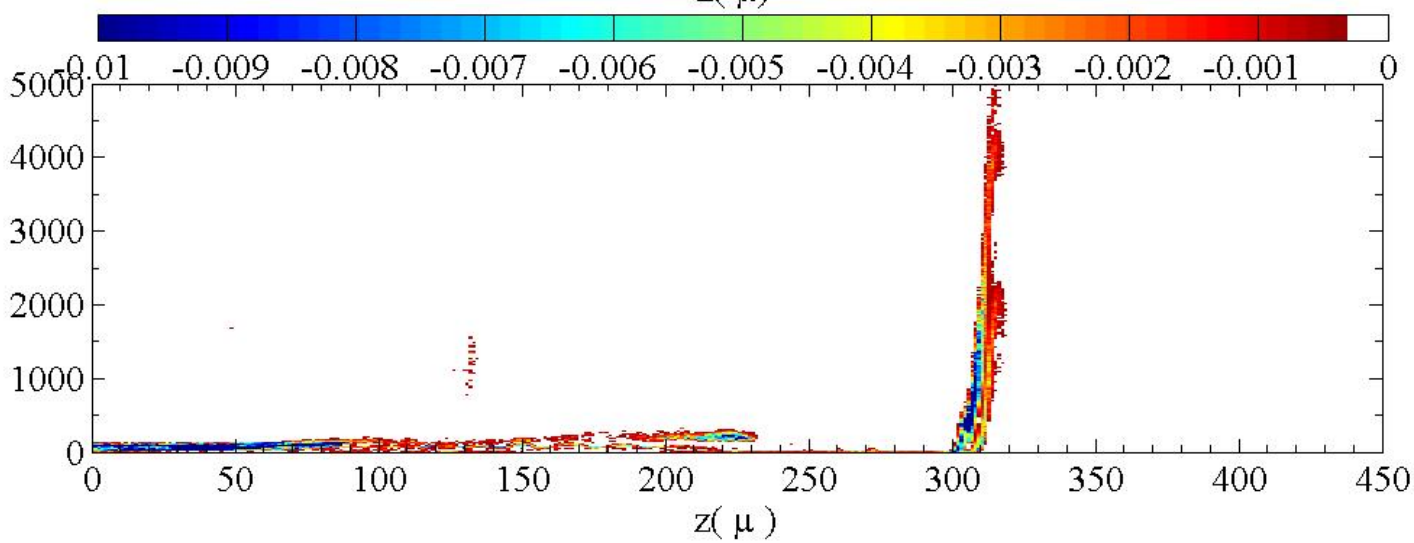
He electrons do and reach energies up to 2.3 GeV

OSIRIS Simulation:
Phase Space (P_z-z) Of Li & He Electrons and the on-axis line out of the E_z

Li electrons do not get trapped

Li at
z=11.3 cm





He at
z=21 cm

He electrons do and reach energies up to 2.5 GeV