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BIG PHYSICS GETS SMALL

Recent Work on

Laser and Beam - Driven Wakefield Acceleration

Chan Joshi
University of California Los Angeles
USA

Supported by US DOE

,

UCLA

UCLA Program on Plasma Based Accelerators
C. Joshi, P.I.
W. Mori, Co-P.I.
C. Clayton, Co-P.I.
2005-Present

EXPERIMENTS

Dr. Chris Clayton
Dr. Sergei Tochitsky
Ken Marsh
Jay Sung, Neptune Lab, graduated
Joe Ralph, Neptune Lab, graduated
Fang Fang, Terawatt Lab, graduated
Dan Haberberger, Neptune Lab
Art Pak, Terawatt Lab
Tyan-lin Wang, LLNL
2 students to be recruited for SLAC

THEORY & SIMULATIONS

Prof. Warren Mori
Chengkun Huang, graduated
Wei Lu, graduated
Miaomiao Zhou, graduated
M.Tzoufras , graduated
Weiming An

Collaborators:

Professors Musumeci, Rosenzweig & Pellegrini (UCLA)
Dr. M. Hogan (SLAC)
Professors T. Katsouleas, P. Muggli (Duke & USC)
Dr. Dustin Froula (LLNL)
Professor Luis O Silva (IST)

Alumni of UCLA Plasma Accelerator Group

Still active in Plasma Acceleration (1985- present)

C.E..Clayton UCLA	(1983-present)
T.Katsouleas, Dean of Engineering Duke University	(1984-1989)
Warren Mori, Professor UCLA	(1982-present)
Don Umstadter, Professor U.Nebraska/U.Michigan	(1982-1987)
Wim Leemans, Head L'Oasis Lab LBNL	(1987-1991)
Yoniyoshi Kitagawa, Professor Osaka U/Hama'tsu	(1988-1989)
Ron Williams, Professor FA&M	(1986-1992)
Patric Muggli, Research Professor USC	(1992-1996)
Dan Gordon, NRL	(1992-1997)
Catalin Filip Spectra Physics	(1997-2003)
Luis O Silva Professor IST Portugal	(1995-1998)
Wei Lu, Researcher UCLA	(2000-2006)
Chengkun Huang, Researcher LANL	(2001-2007)
J . Ralph, Researcher LLNL	(2001-2008)
M . Tzoufras Oxford	(2000-2007)

Also J. M . Dawson, F .F. Chen, T Tajima, P . Chen (Prior to 1985)

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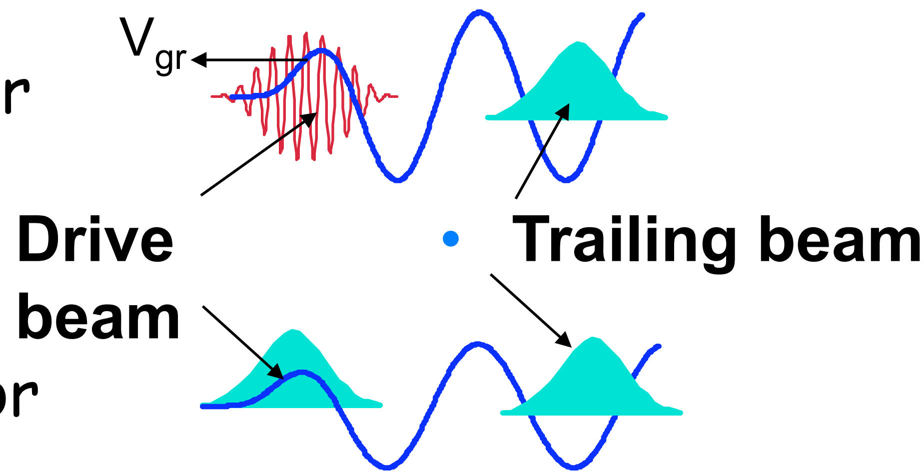
Plasma Based Accelerators

- Laser Wake Field Accelerator

  A single short-pulse of photons



Plasma Wake Field Accelerator

A high energy electron bunch

- Wake: phase velocity = driver velocity

Large wake for a laser amplitude $a_o = eE_o/m\omega_o c \sim 1$ or a beam density $n_b \sim n_o$

For τ_{pulse} of order $\pi\omega_p^{-1} \sim 100fs\,(10^{17}/n_o)^{1/2}$ and spot size c/ω_p:

$P \sim 15$ TW $(\tau_{pulse}/100\text{ fs})^2$ laser

T.Tajima and J.M.Dawson PRL(1979)

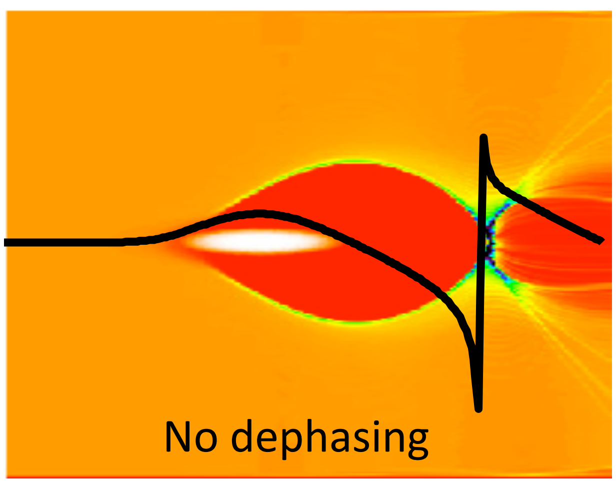
P.Chen et.al.PRL(1983)

Blowout and Bubble Formation Regime

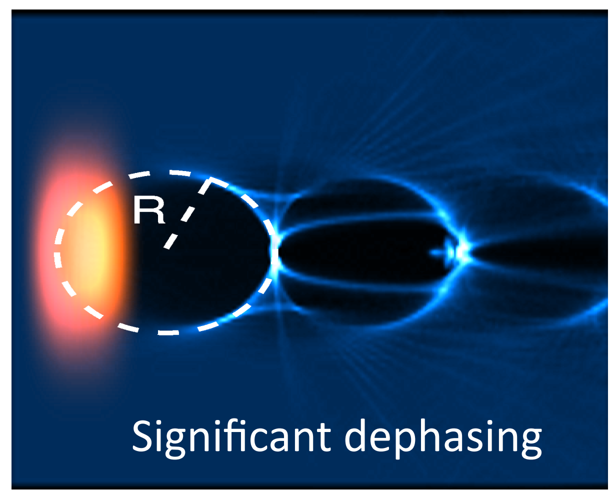
Rosenzweig et al. 1990   Puhkov and Meyer-te-vehn 2002

- Ion channel formed by complete evacuation of plasma electrons
- Ideal linear focusing force
- Uniform acceleration in transverse dimension

Beam driver



Laser driver



Intense Beams of Electrons for Plasma Wakefield Acceleration

Only place in the world to study this topic !!

SLAC NATIONAL ACCELERATOR LABORATORY
New SLAC National Accelerator Laboratory logo

N = 4 x 10^{10}

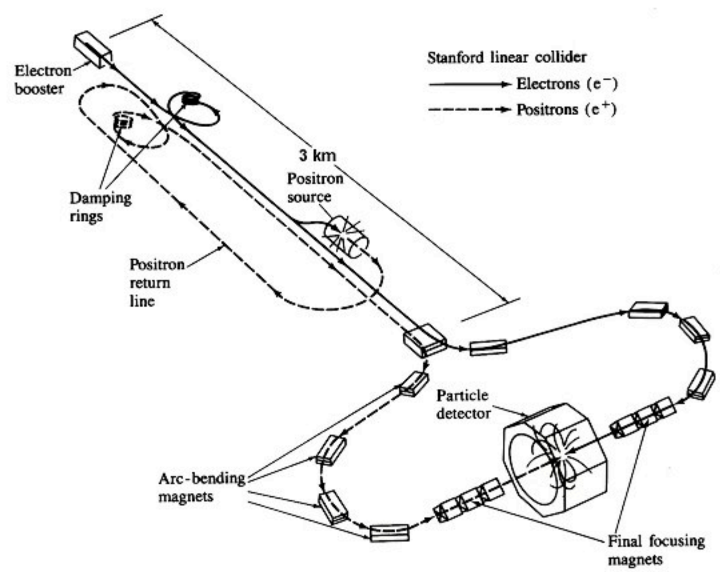
Energy 50 GeV

Rep Rate 60 HZ

Energy/pulse 320 J
Focal Spot Size 10 microns

Pulse Width 50 fs

Focused Intensity 7 x 10^{21} W/cm^2



Comparable to the most intense laser beams to-date

PWFA : Present Collaborators

* B. Allen	USC
* W. An	UCLA
* K. Bane	SLAC
* L. Bentson	SLAC
* I. Blumenfeld	SLAC
* C.E. Clayton	UCLA
* S. DeBarger	SLAC
* F.-J. Decker	SLAC
* R. Erickson	SLAC
* R. Gholizadeh	USC
* M.J. Hogan	SLAC
* C. Huang	UCLA
* R.H. Iverson	SLAC
* C. Joshi	UCLA
* T. Katsouleas	Duke University
* N. Kirby	SLAC
* N. Li	SLAC
* W. Lu	UCLA
* D.B. MacFarlane	SLAC
* K.A. Marsh	UCLA
* W.B. Mori	UCLA
* P. Muggli	USC
* Y. Nosochkov	SLAC
* S. Pei	SLAC
* T.O. Raubenheimer	SLAC
* J.T. Seeman	SLAC
* A. Seryi	SLAC
* R.H. Siemann	SLAC
* P. Tenenbaum	SLAC
* J. Vollaire	SLAC
* D. Walz	SLAC
* X. Wang	USC
* W. Wittmer	SLAC

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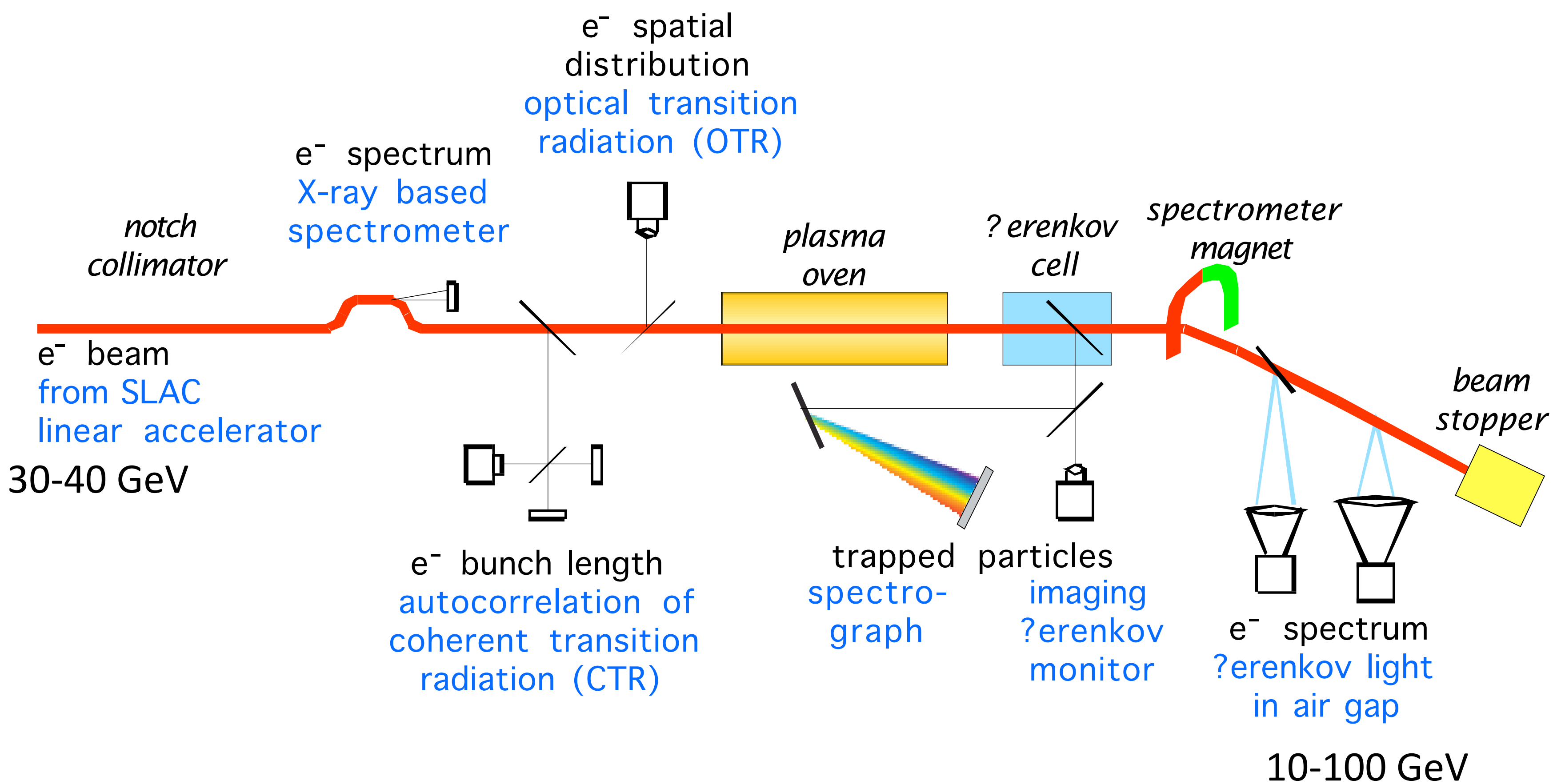
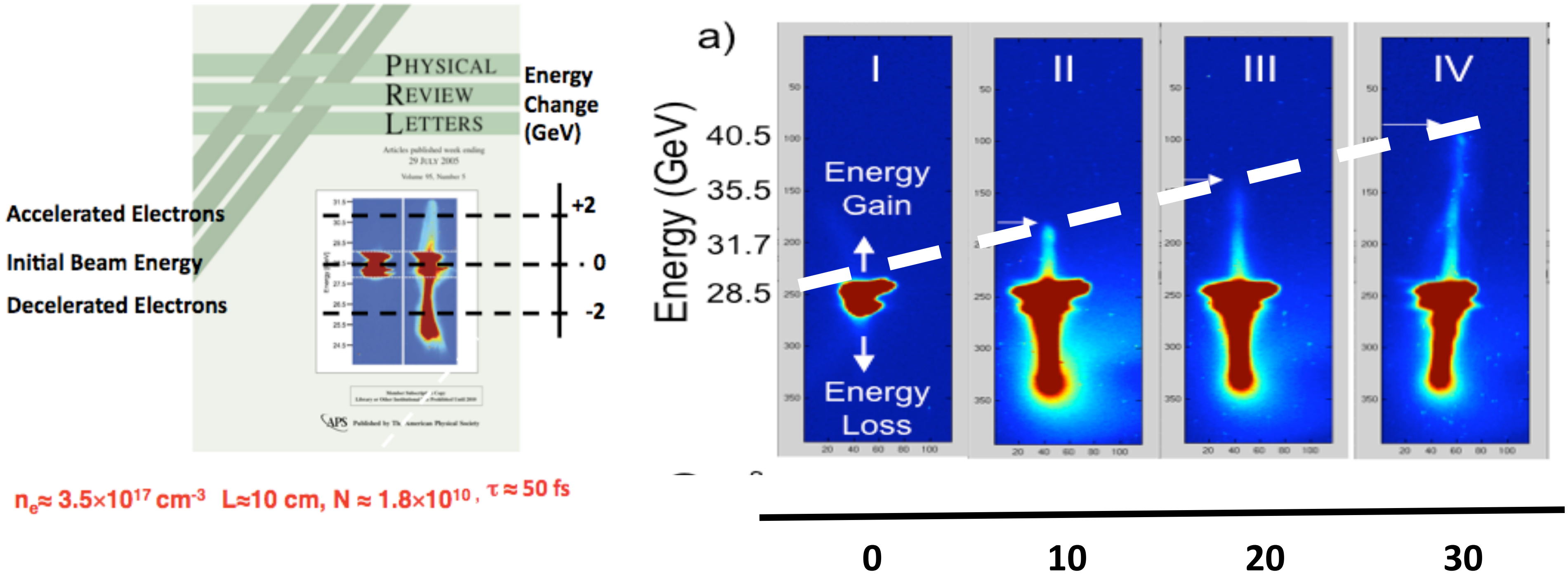
Experimental Setup



Energy Gain Scales Linearly with Length



$n_e \approx 3.5\times10^{17}\ cm^{-3}$ $L\approx10$ cm, $N \approx 1.8\times10^{10}$, $\tau \approx 50$ fs

BREAKING THE 1 GeV BARRIER

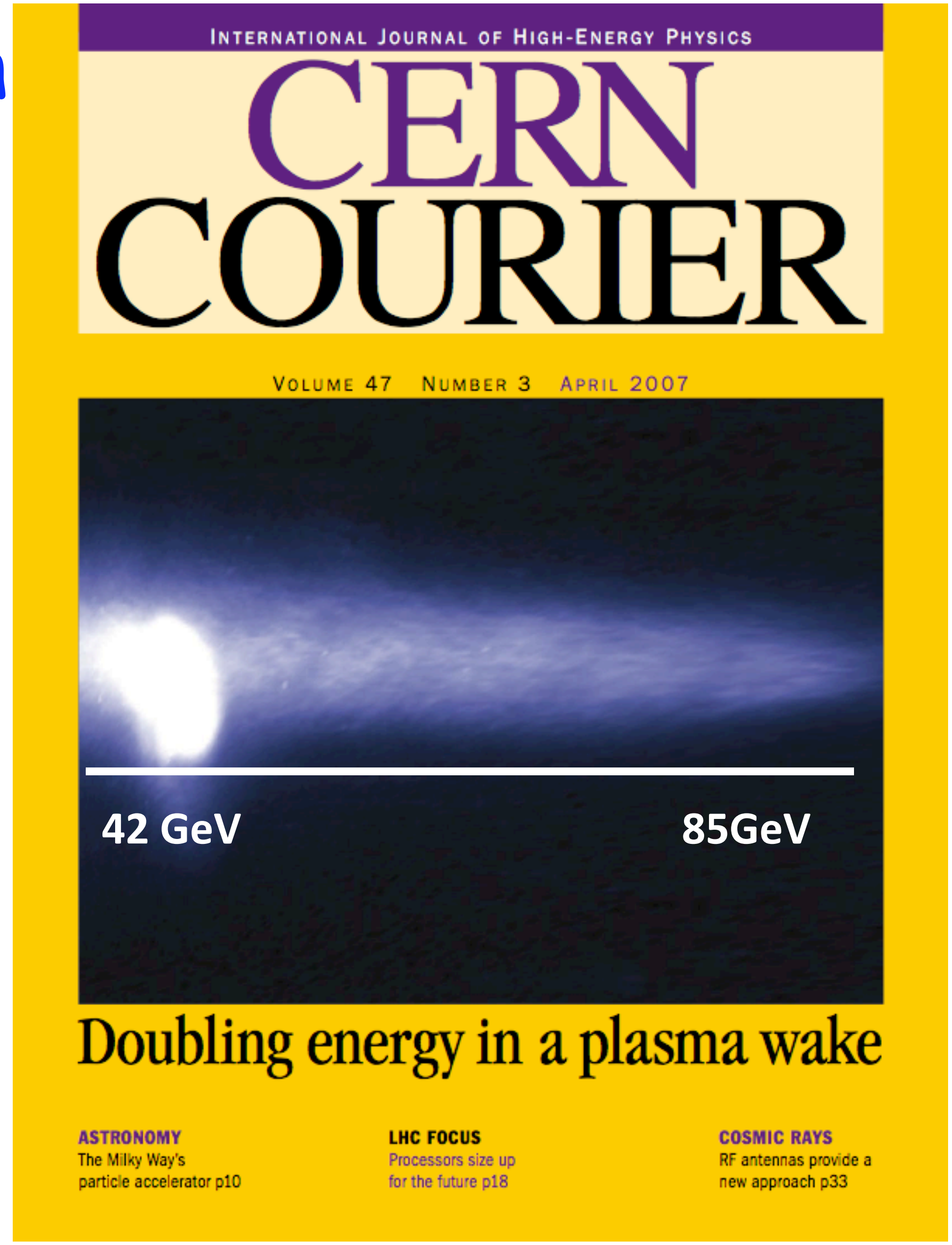
PLASMA LENGTH (cm)

No phase slippage between particles themselves and between particles and wake

M.Hogan et al Phys Rev Lett (2005)

Spectacular Progress in Plasma Wakefield Acceleration

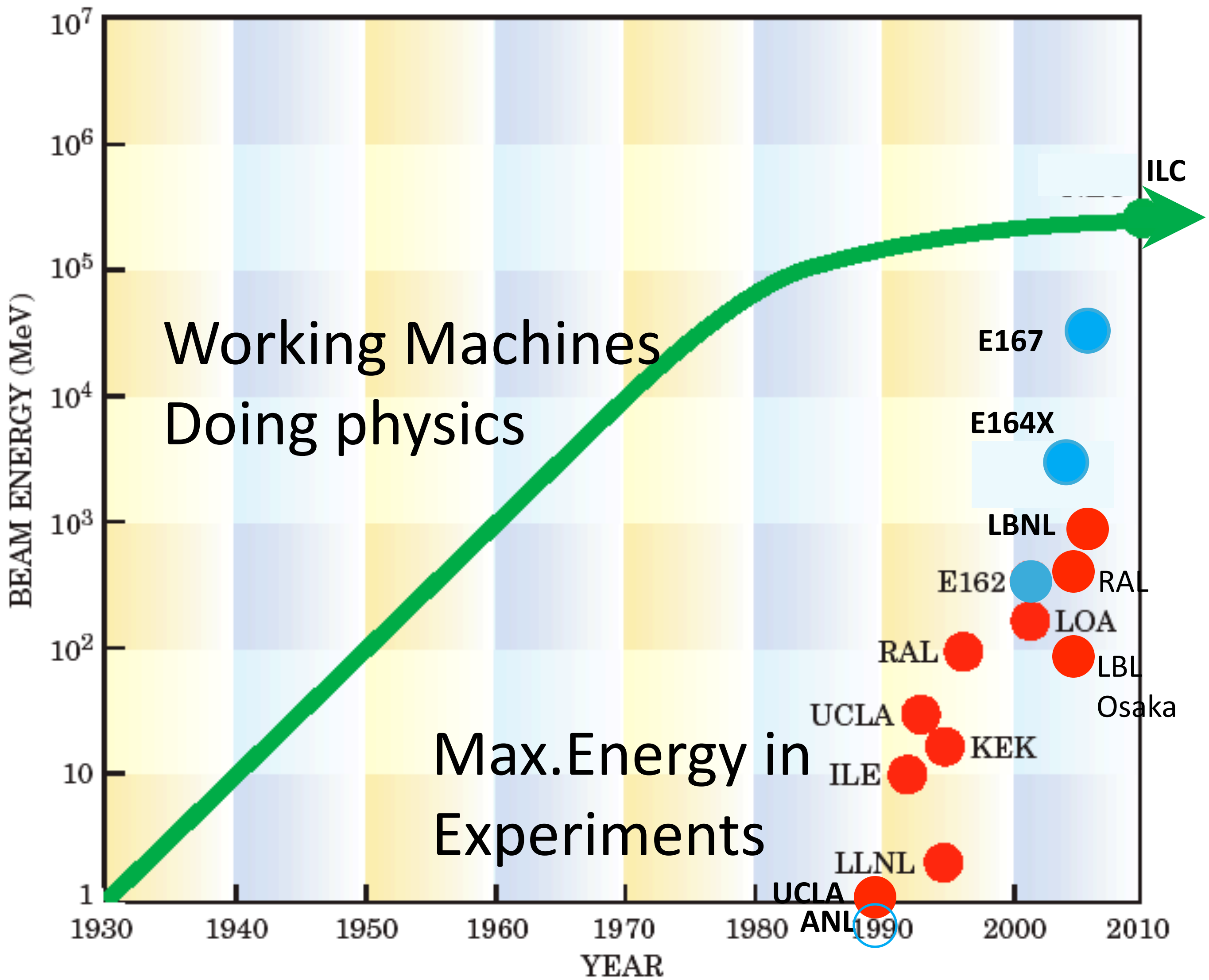
Energy Doubling of 42 Billion Volt Electrons Using an 85 cm Long Plasma Wakefield Accelerator



Nature v 445,p741 (2007)

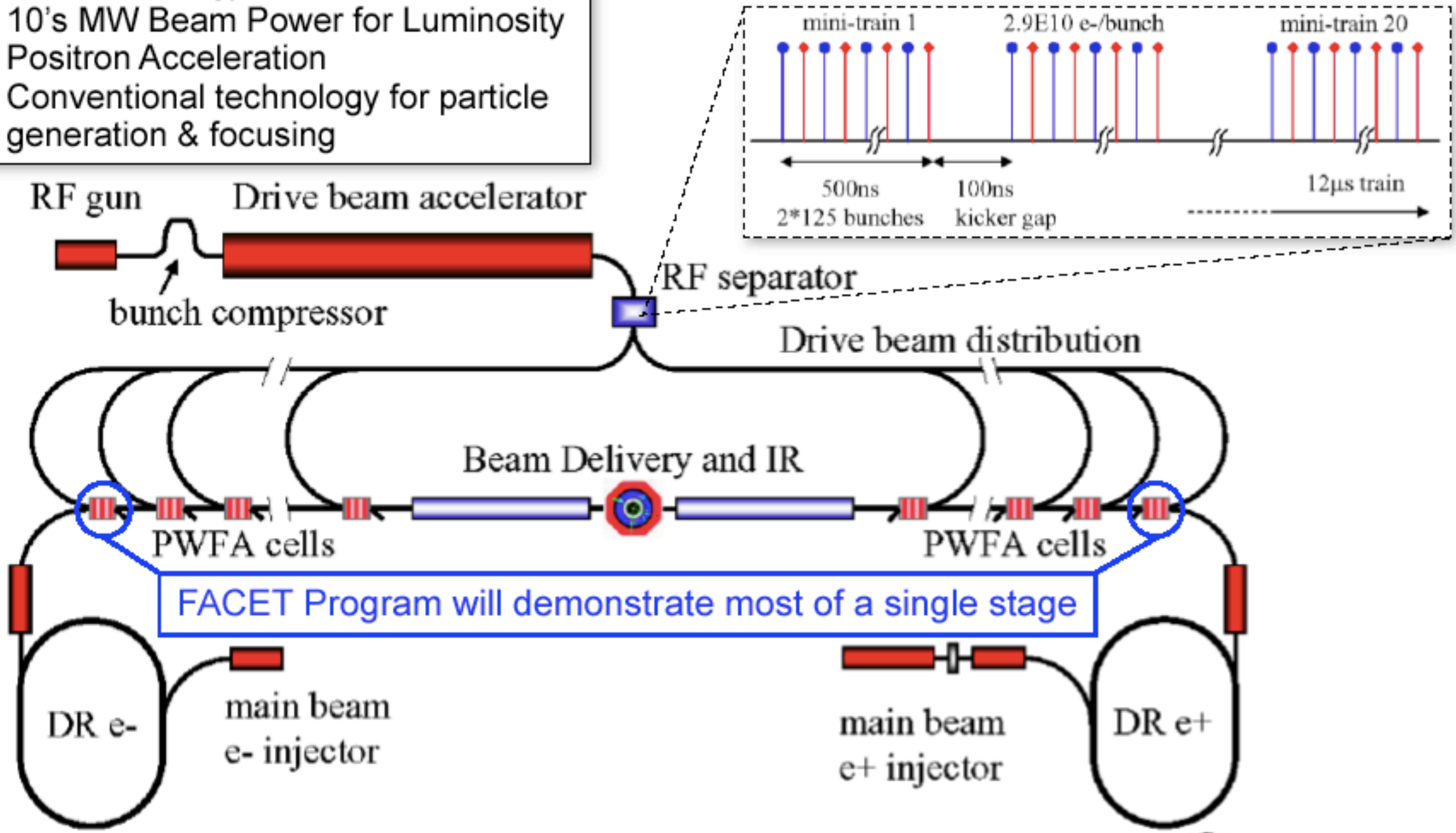
Plasma Accelerator Progress

"Accelerator Moore's Law"

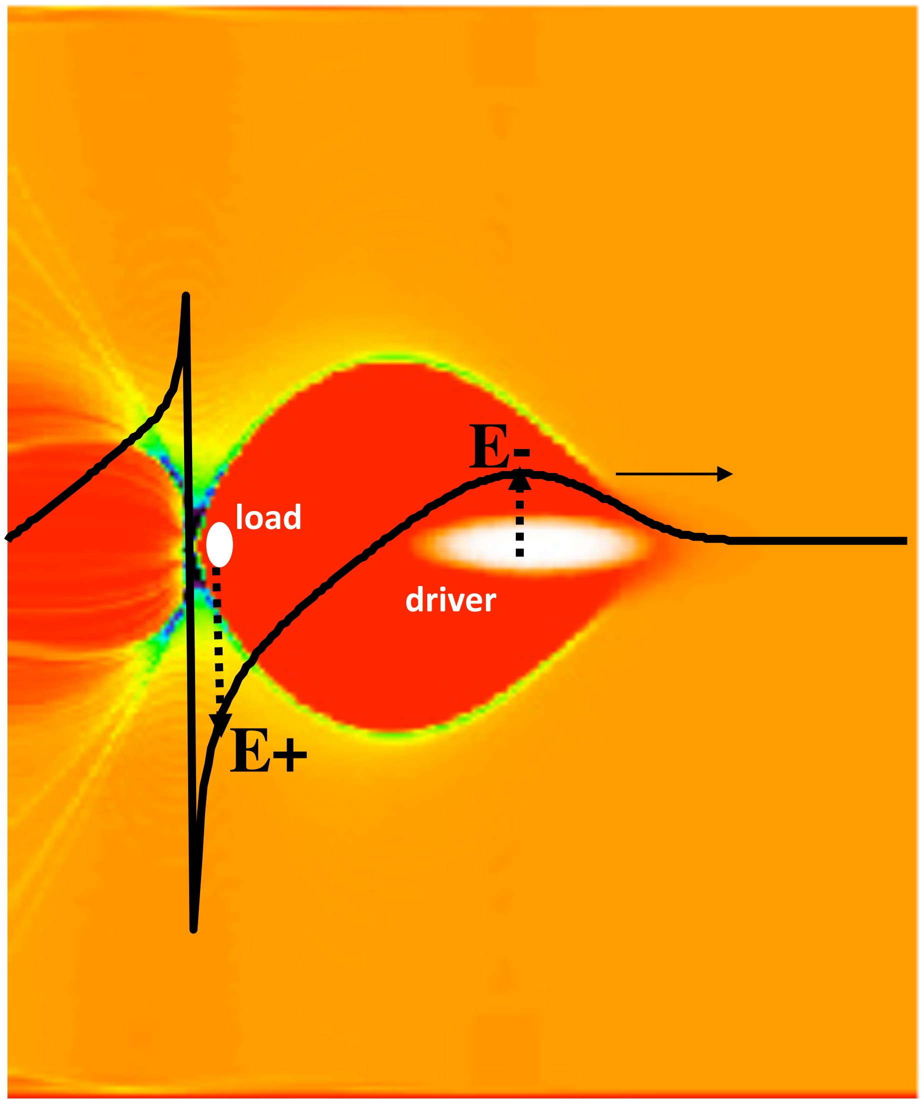


A Concept for a Plasma Wakefield Accelerator Based Linear Collider

- TeV CM Energy
- 10's MW Beam Power for Luminosity
- Positron Acceleration
- Conventional technology for particle generation & focusing



Generation of High Quality Beams



The most pressing goal is the demonstration of one stage of a 10-25 GeV plasma accelerator module with small energy spread & emittance and at least 1nC charge.

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Beam-Plasma Accelerators: Where to next?

FACET : Facility for AA Research @SLAC

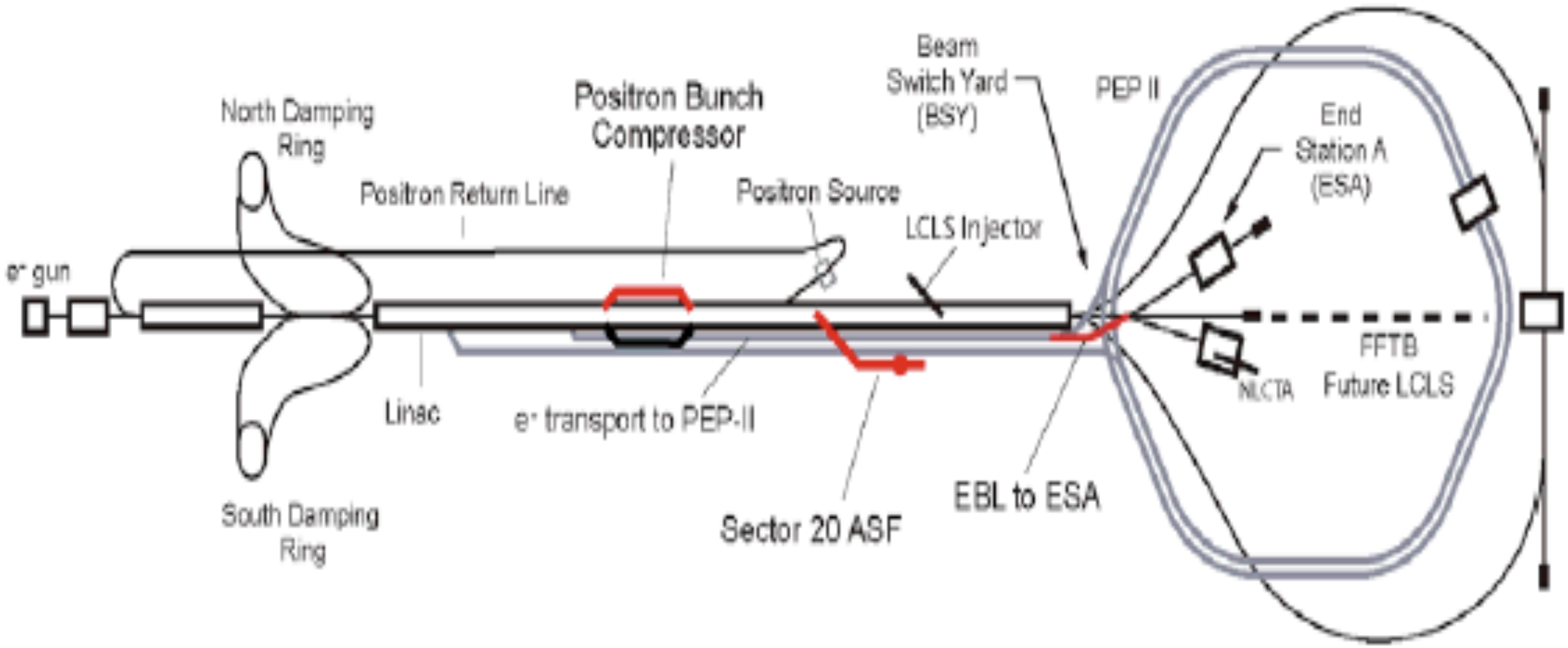

Figure 1-1. Schematic of the SLAC site with proposed FACET modifications to the beam delivery systems.

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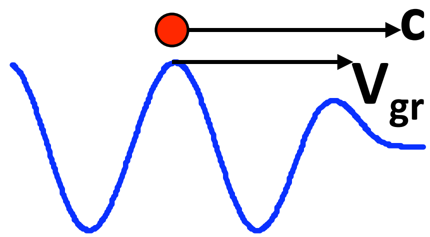
Laser Wakefield Accelerator

Limits to Energy Gain $W = eE_z L_{acc}$

- **Diffraction:** $L_{dif} \cong \pi L_R = \pi^2 w_0^2 / \lambda$

  order mm!
  (but overcome w/ channels or relativistic self-focusing)

- **Dephasing:**



$$L_{dph} = \frac{\lambda_p / 2}{1 - V_{gr}/c}$$

order 10 cm x $10^{16}/n_o$

- **Depletion:** For $a_0 > 1$ $L_{dph} \sim L_{depl}$

Need to increase the electron-wake interaction length

Self Guiding Could Simplify GeV- Class LWFA

- Self-Guiding of Laser Pulses in the Blowout Regime J.Ralph et al PRL 102,175003 (2009)

- Quasi-Monoenergetic Electron Acceleration to 720 MeV using Callisto Laser at LLNL.
  D.Froula et al to be published PRL (2009)

- Ionization Induced Trapping for Injecting electrons in Low Density Wakes.
- A.Pak et al PRL submitted (2009)

. Experiments for Extending the Self-Guided Regime to beyond 1 GeV. (UCLA/LLNL collaboration : Unpublished)

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Self-Guiding in the Blow-Out Regime

Blowout Condition: $a_0 > 2$

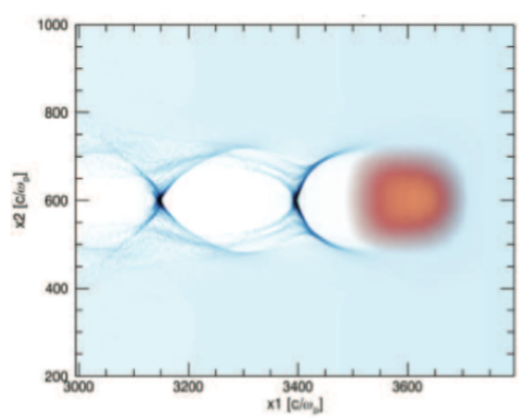
Guiding Condition: $\left(\frac{\delta n}{n}\right) \geq \frac{4}{\left(k_p W_0\right)^2} \Rightarrow \left(k_p W_0\right) \geq 2$

This gives a minimum density where self-guiding can occur for a given W_0

Matching Condition[1]: $k_p R_b \approx k_p W_{match} \approx 2\sqrt{a_0}$

Matched spot size

Pulse evolution is minimized if this is satisfied. For W_0 close to this size the pulse is predicted to reach a steady state at $W_{matched}$



1. W. Lu, C. Huang, M. Zhou, M. Tzoufras, F. S. Tsung, W. B. Mori, and T. Katsouleas, Phys. Plasmas **13**, 056709(2006)

Physical picture of Self guided LWFA

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The accelerating structure needs to remain as stable, for this purpose we choose the laser spot size and intensity from the condition :

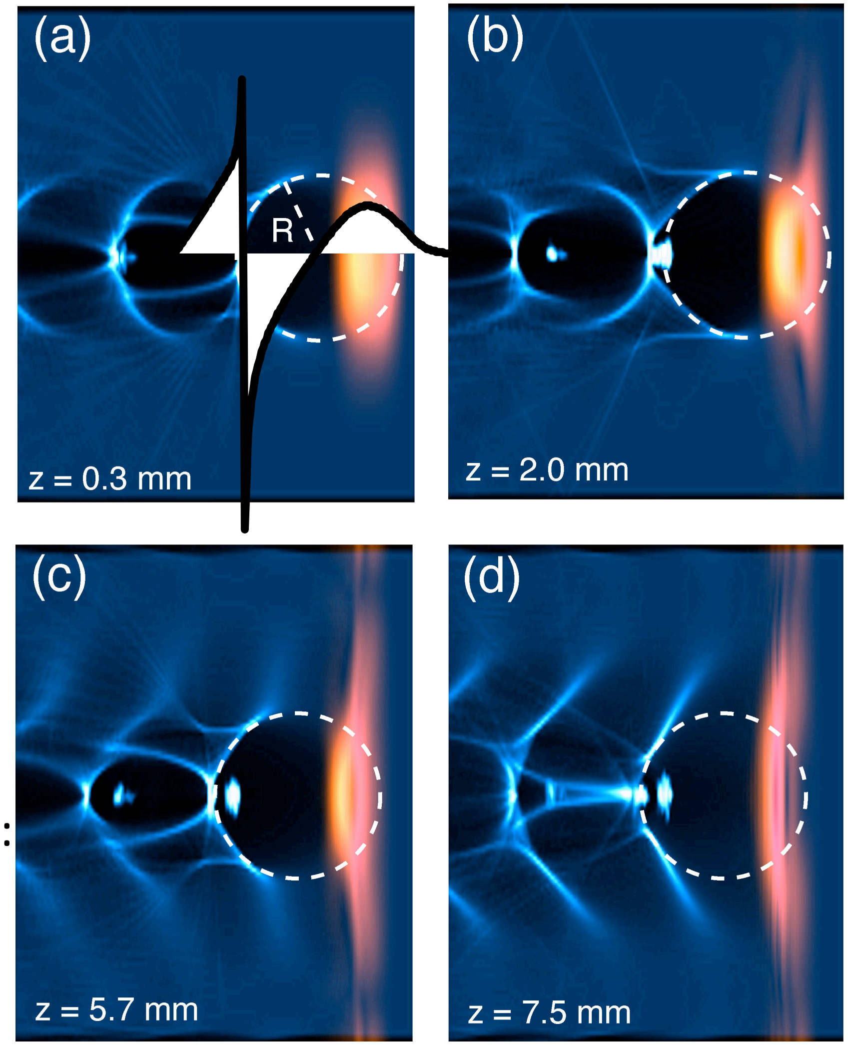
$$\begin{bmatrix}\text{Matched}\\ \text{profile}\end{bmatrix}: \; k_p w_0 \approx k_p R_b \approx 2\sqrt{a_0} \Rightarrow a_0 \approx 2\left(\frac{P}{P_c}\right)^{1/3}$$

The accelerating field in the ion channel decreases linearly from the front reaching minimum value with magnitude:

$$\begin{bmatrix}\text{Maximum}\\ \text{field}\end{bmatrix}: \; \frac{eE_M}{mc\omega_p} \approx \frac{1}{2} k_p R_b \approx \sqrt{a_0}$$

The acceleration process is limited by dephasing:

$$\begin{bmatrix}\text{Acceleration}\\ \text{distance}\end{bmatrix}: \; \begin{matrix} a_0 > 1 \\ L \approx R_b \end{matrix} \Rightarrow L_{etch} \geq L_{\phi} \approx \frac{4\sqrt{a_0}}{3k_0}\left(\frac{k_0}{k_p}\right)^3$$



Parameter design for GeV and beyond for LWFA

Callisto Laser at LLNL : 300 TW Maximum Power

	$P(PW)$	$\tau(fs)$	$n_p\ (cm^{-3})$	$w_0\ (\mu m)$	$L(cm)$	$a0$	$Q(nC)$	$E(GeV)$
Current	0.100	60	2.0×10^{18}	15	0.9	3.78	0.40	1.06
Planned	0.250	60	1.0×10^{18}	20	1.0	3.15	0.30	2.0

Wei Lu et.al. PRST-AB 07

Collaborators

LLNL

- D. Froula
- F. Albert
- P. Michel
- L. Divol
- T. Doeppner
- J. Palastro
- J. Bonlie
- D. Price

UCLA

- C. Clayton
- K. Marsh
- A. Pak
- W. Lu
- J.Ralph
- S.Martins
- W. Mori
- C. Joshi

UCSD

- B. Pollock
- J. S. Ross
- G. Tynan

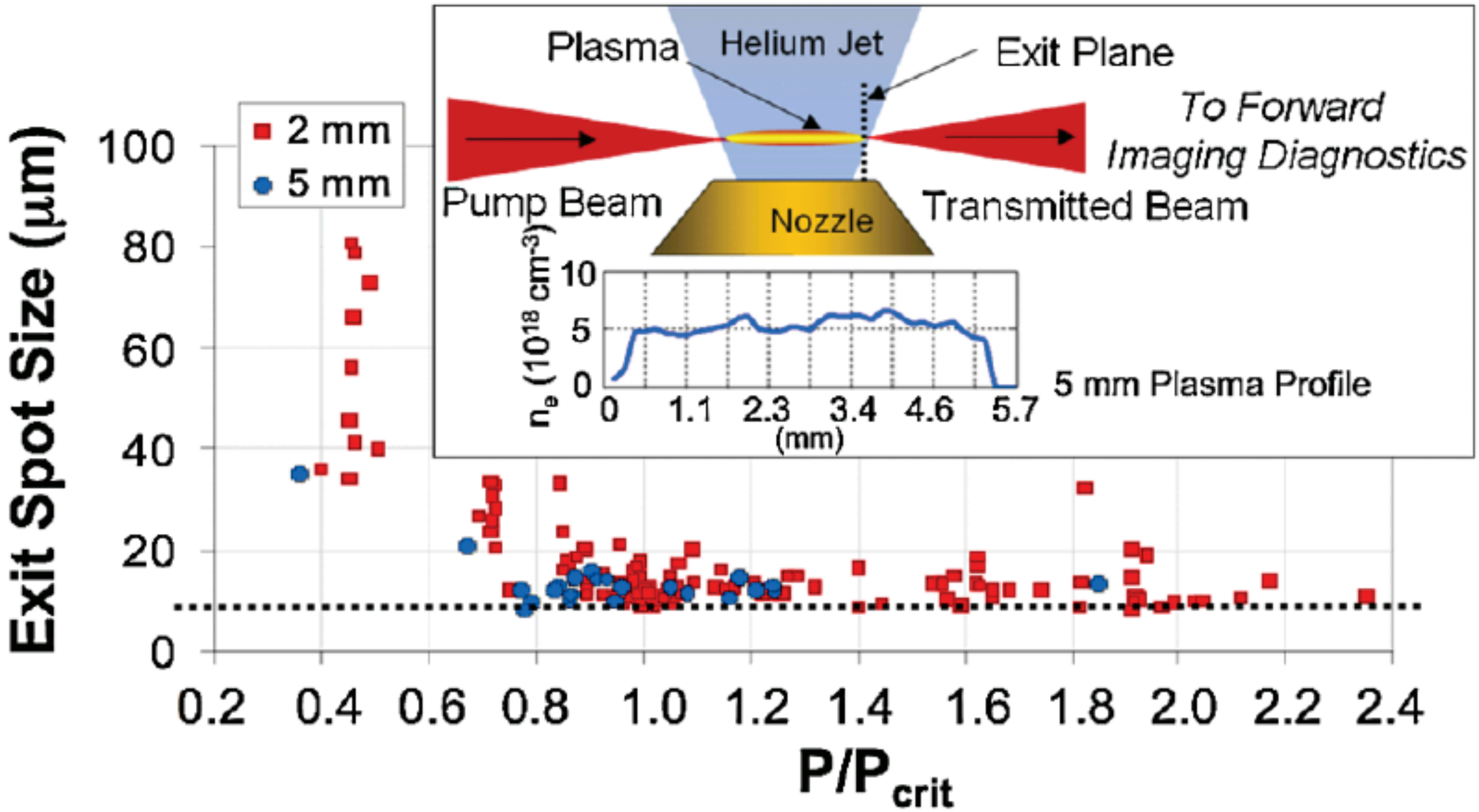
J.Ralph et al Phys Rev Letts (2009)

D.Froula et al , Phys Rev Letts ,accepted (2009)

A.Pak et al , Pys Rev Letts , Submitted (2009)

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344.

Self-Guiding in the Blow-Out Regime



$$P_c \simeq 17(\omega_0/\omega_p)^2 \ \text{GW}$$

J. Ralph et al Phys Rev Letts (2009)

A.G.R. Thomas PRL (2007)

Self-Guiding in Blow-Out Regime

$$k_p R_b \approx k_p W_{match} \approx 2\sqrt{a_0}$$

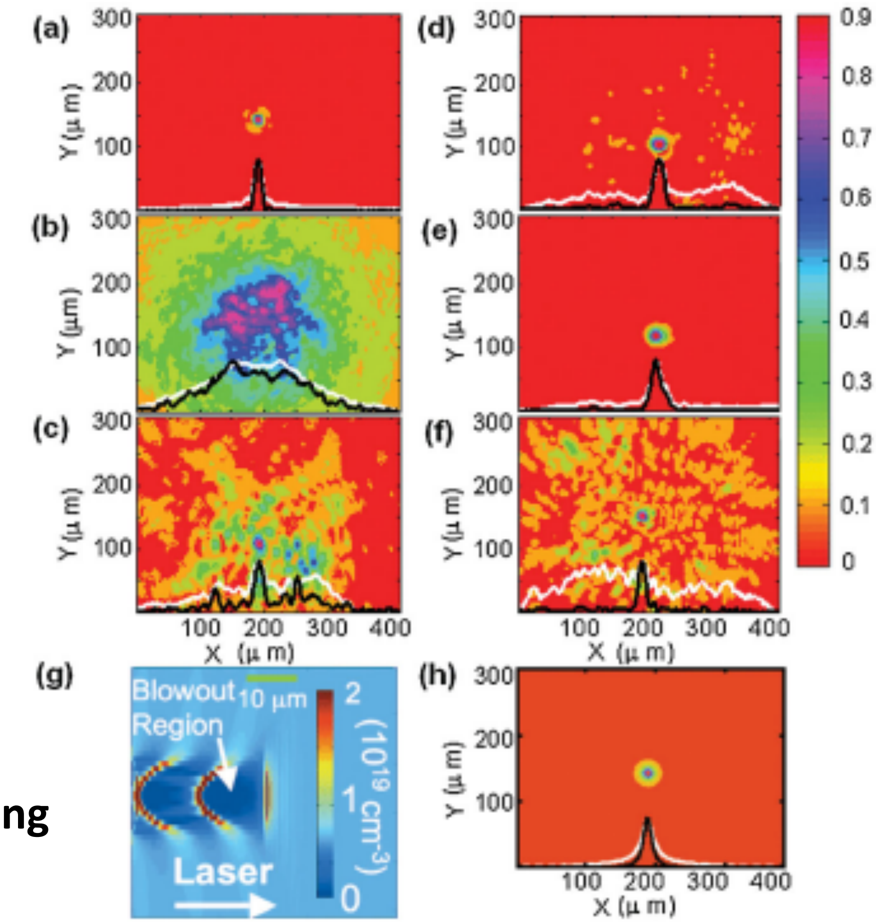
$$k_p w_m = 2\sqrt{2}\left(\frac{P}{P_c}\right)^{1/6}.$$

Laser Spot at entrance

Laser Spot at Exit: No Plasma

Less than matched

PIC Simulation Matched Beam Guiding



Close to matched

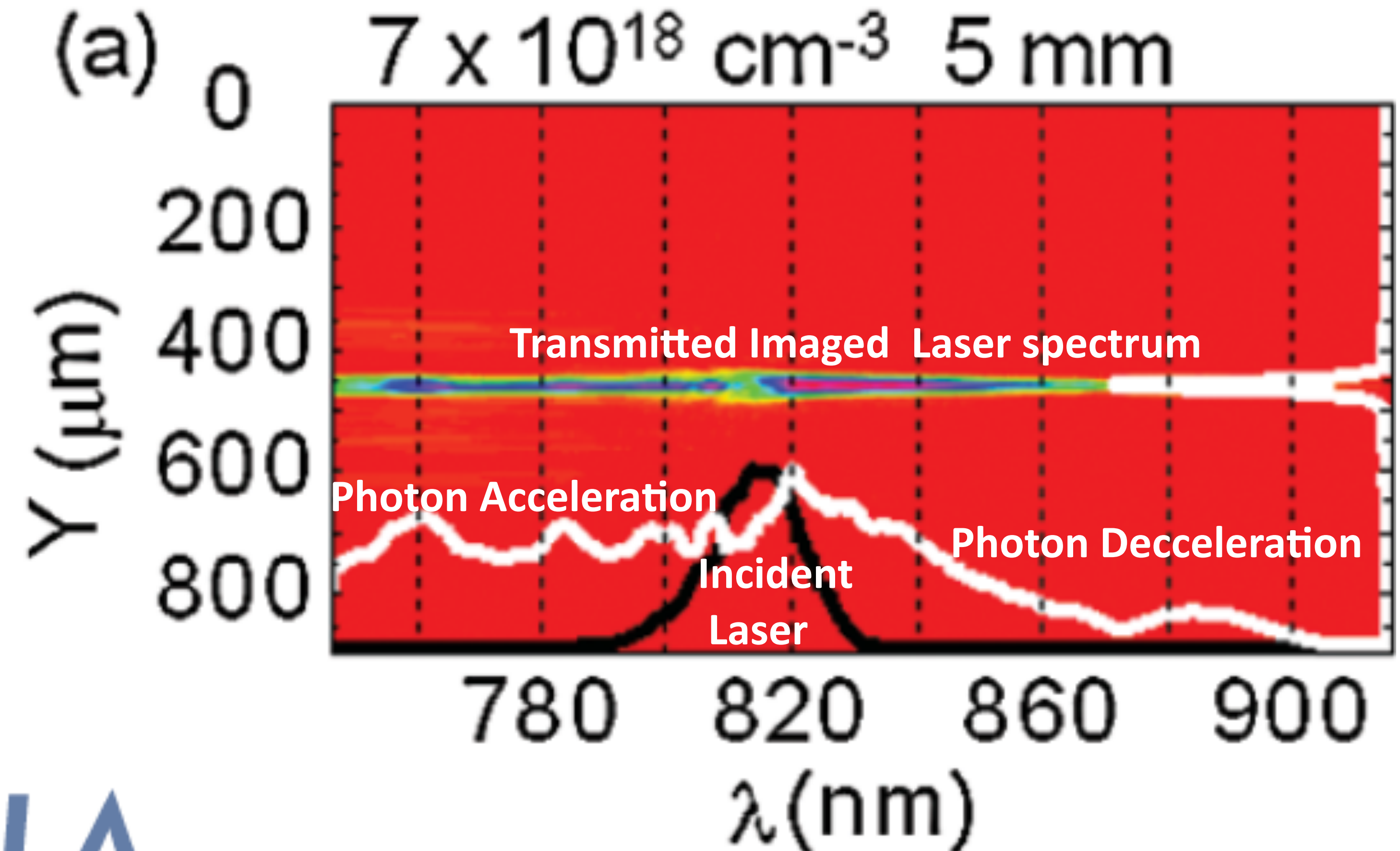
Guided Spot at Matching Condition

Greater than matched

Guided Spot At Exit : Simulations

For a given a_o and laser spot size matching achieved by varying plasma density

Transmitted Laser Spectrum at Matched Density Confirms Self-Guiding



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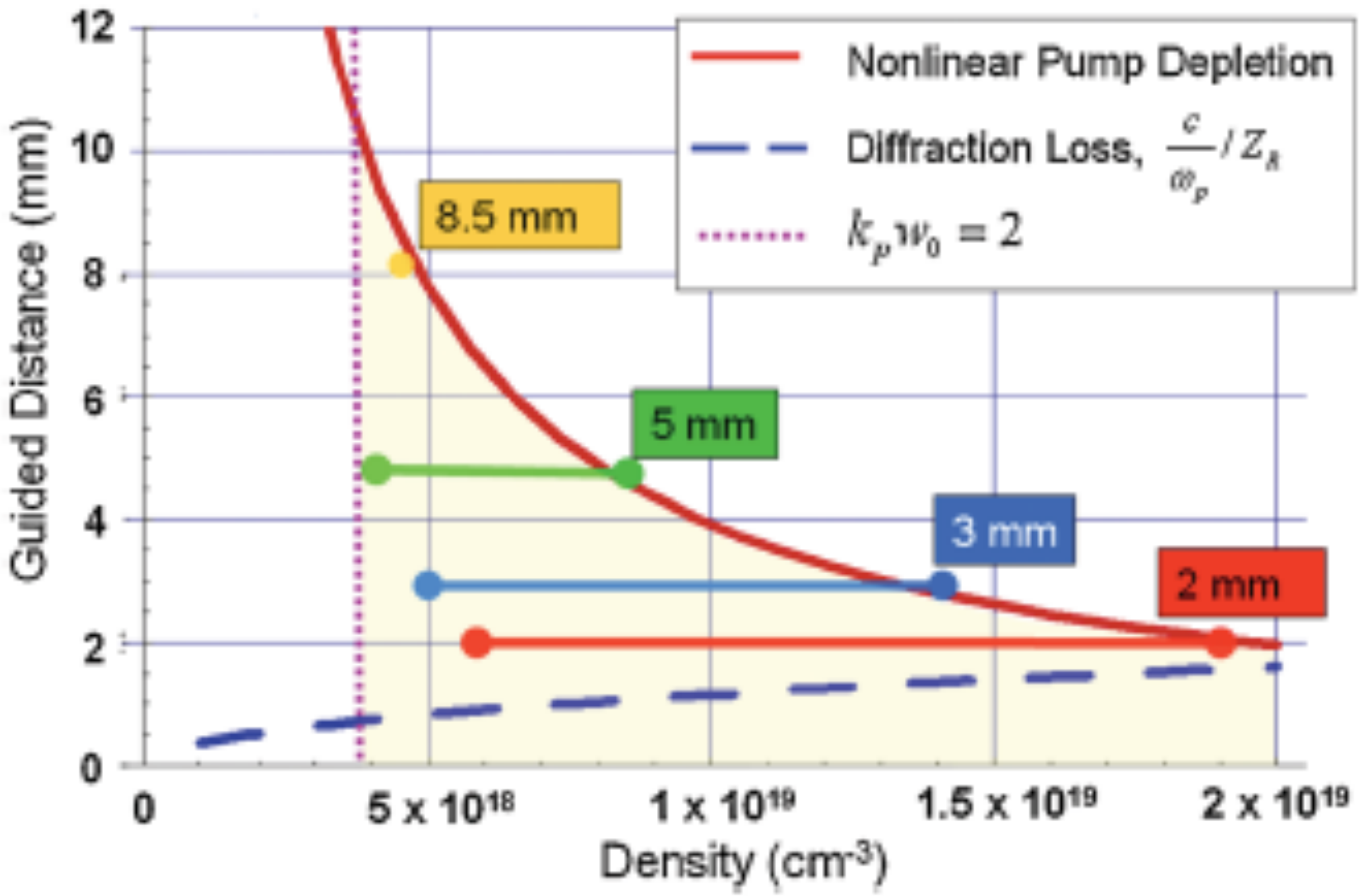
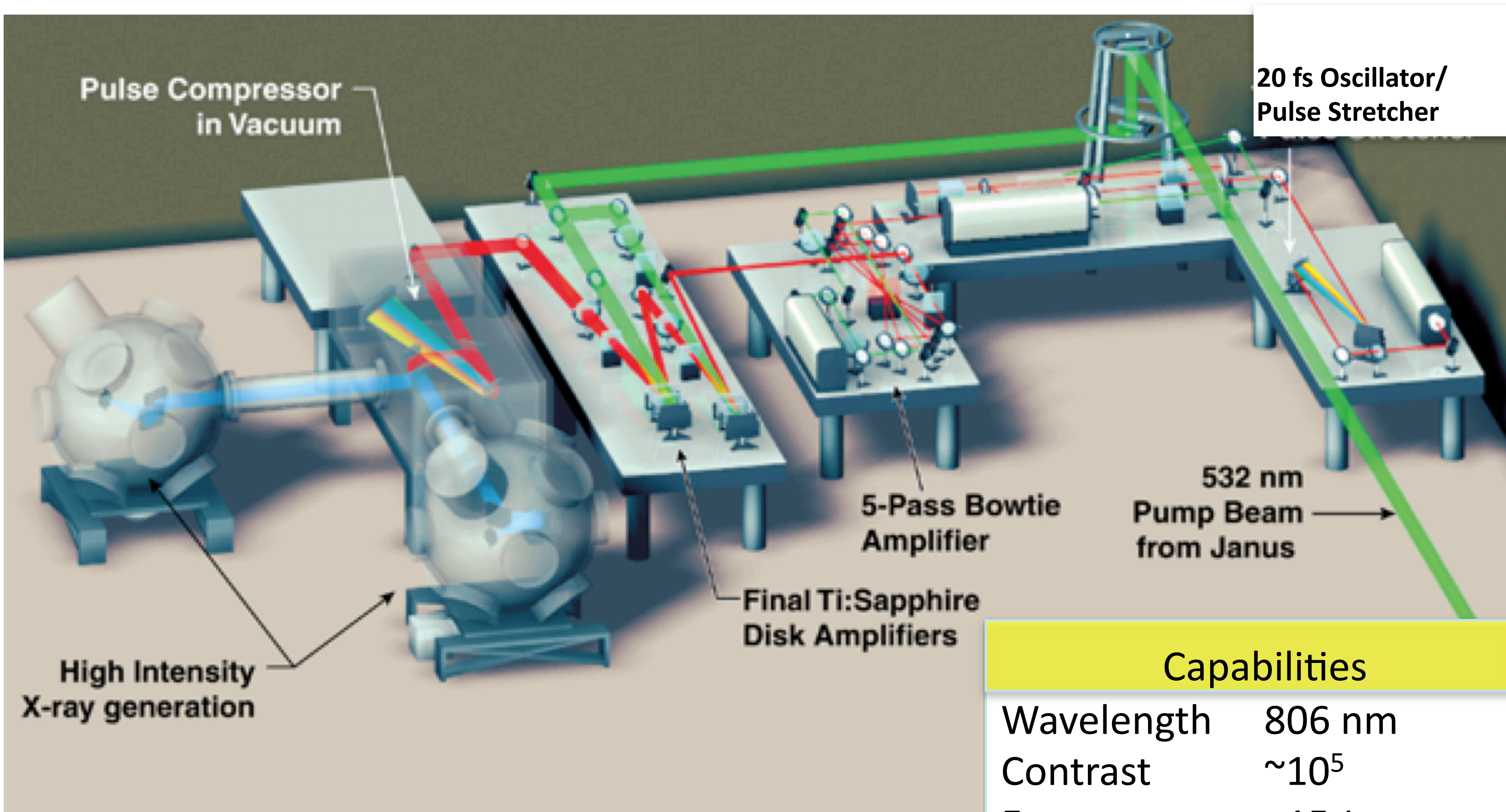
J. Ralph et al Phys Rev Letts (2009)

Pump Depletion Limited Guided Beam propagation of Ultra- short, Intense Laser Pulses



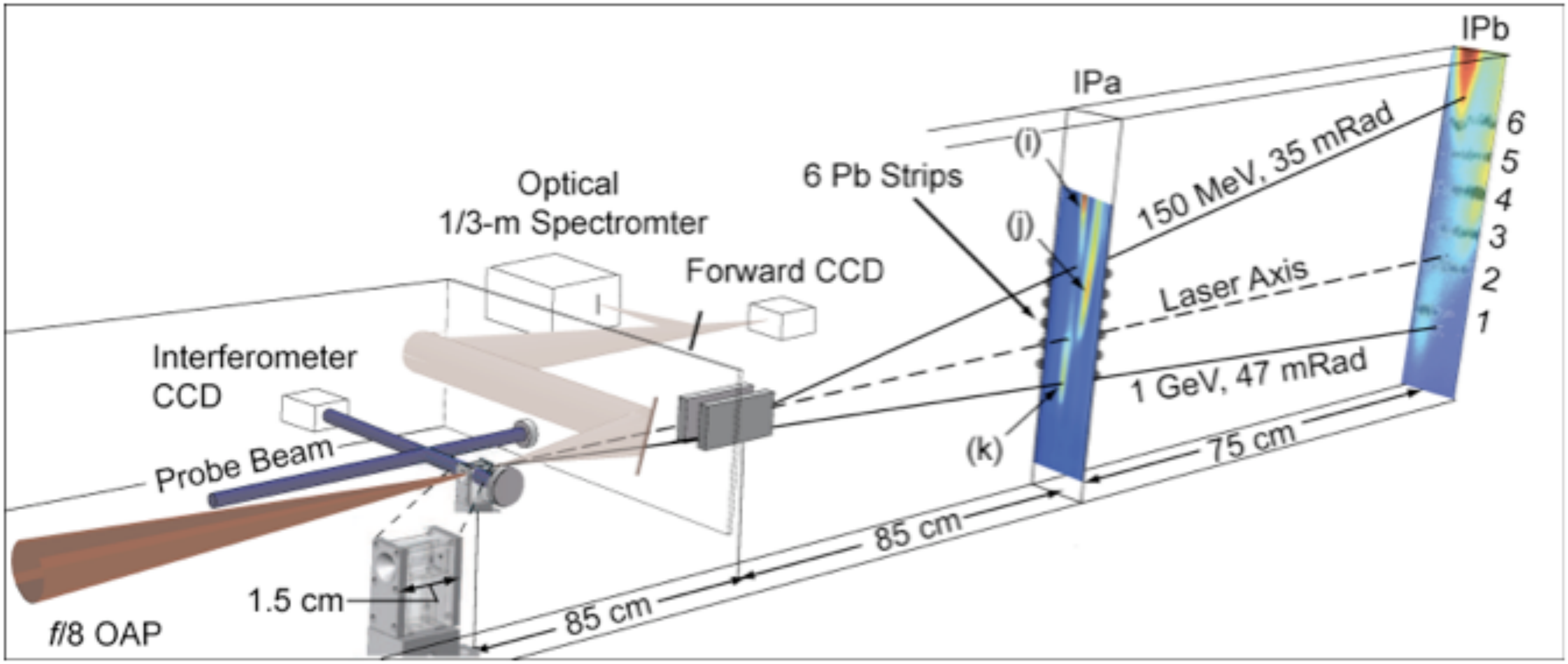
The UCLA/LLNL collaboration : 200 TW Callisto Laser Facility at the Jupiter Laser Facility @ LLNL



Capabilities	
Wavelength	806 nm
Contrast	~10^5
Energy	>15 J
Pulsewidth	<60 fs
Rep rate	2/hour

Self Guided LWFA on Callisto Laser @LLNL

D . Froula et al Phys. Rev. Letts. Submitted 2009



He Gas jet /Gas Cell targets
Up to 15 J in 60 fs , 30% in central spot
Maximum power on target : 80 TW
Dual Screen Spectrometer

Threshold for Self- Trapping in the Self-Guided Regime Measured

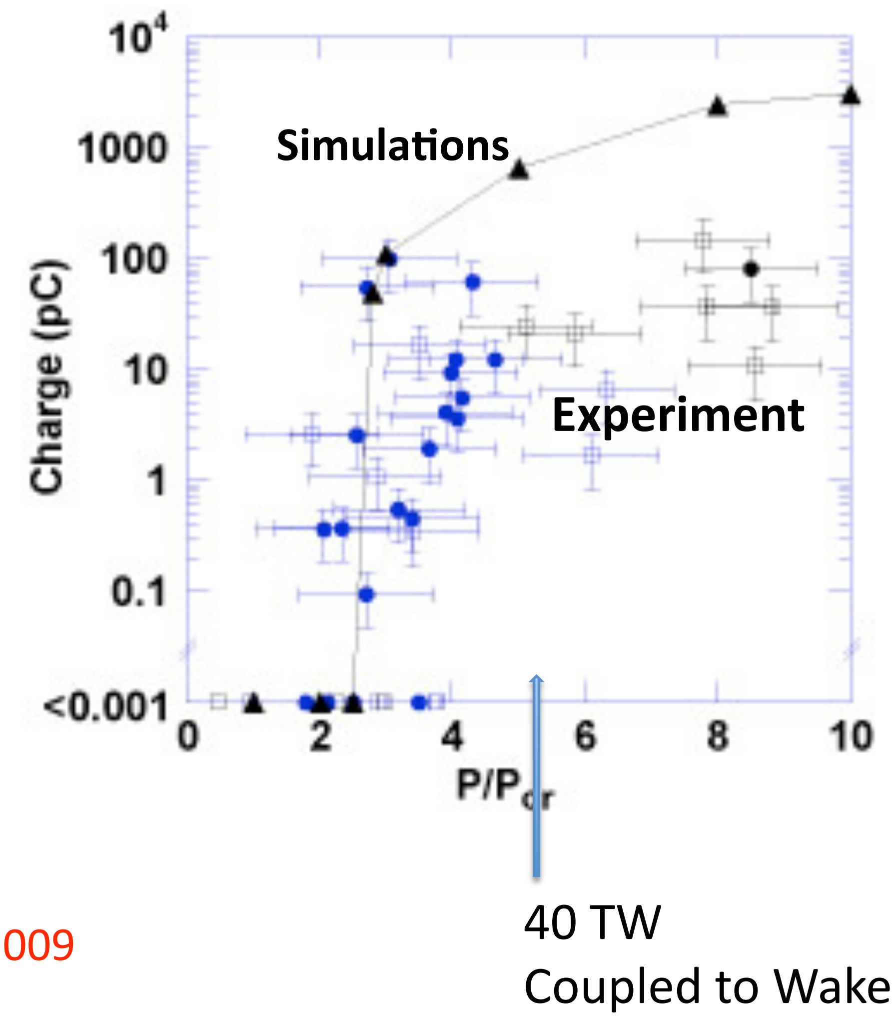
$$P_c \simeq 17(\omega_0/\omega_p)^2 \ \text{GW}$$

Trapping Threshold

P/P_{crit} ~ 3

Saturated Charge

P/P_{crit} ~ 5



D . Froula et al Phys. Rev. Letts. Accepted 2009

A self-injection density threshold is measured at $3x10^{18}$ cm^{-3}

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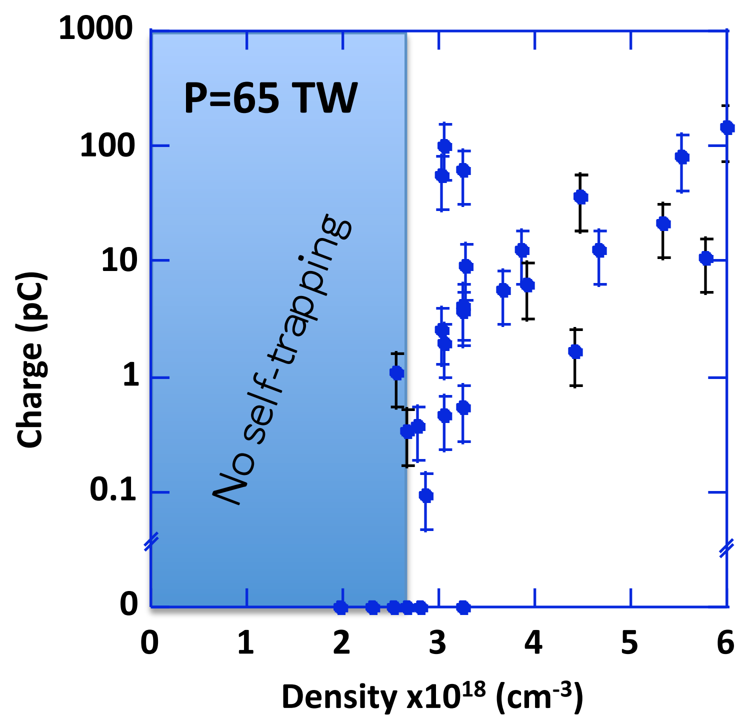
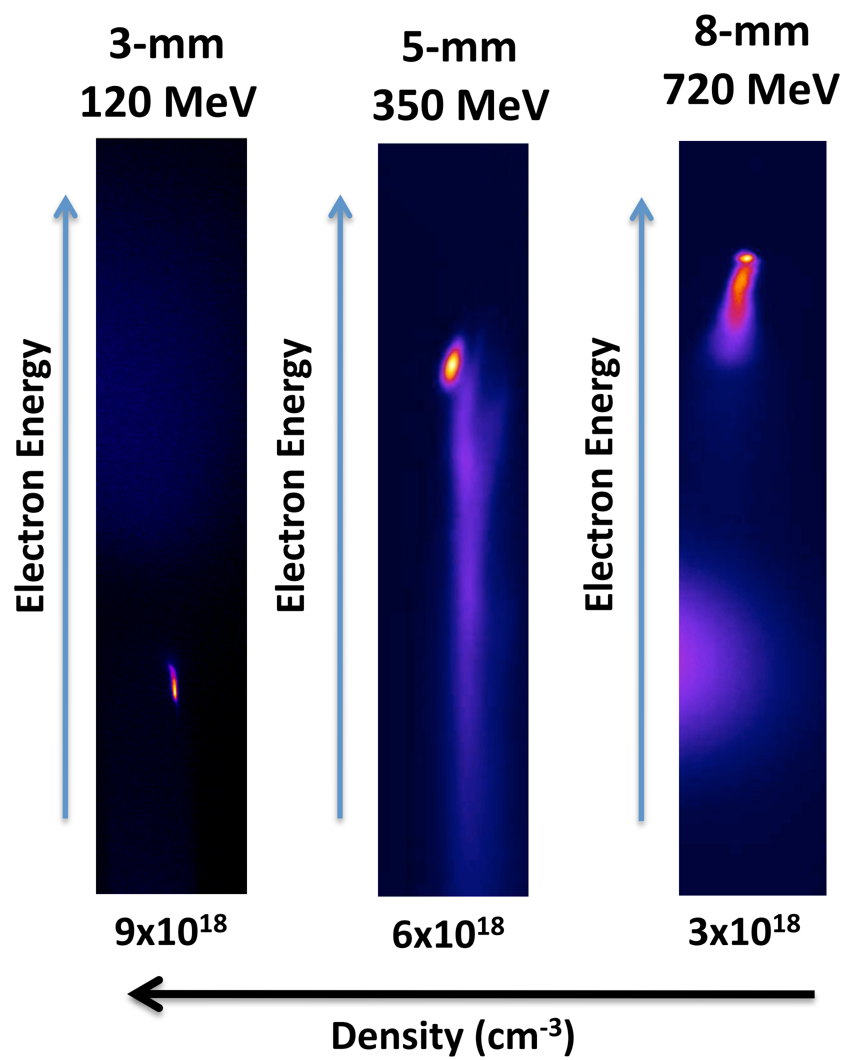
- Image plates are absolutely calibrated for charge
- No electrons were self-injected and accelerated above 100 MeV at densities less than $3x10^{18}$ cm^{-3}



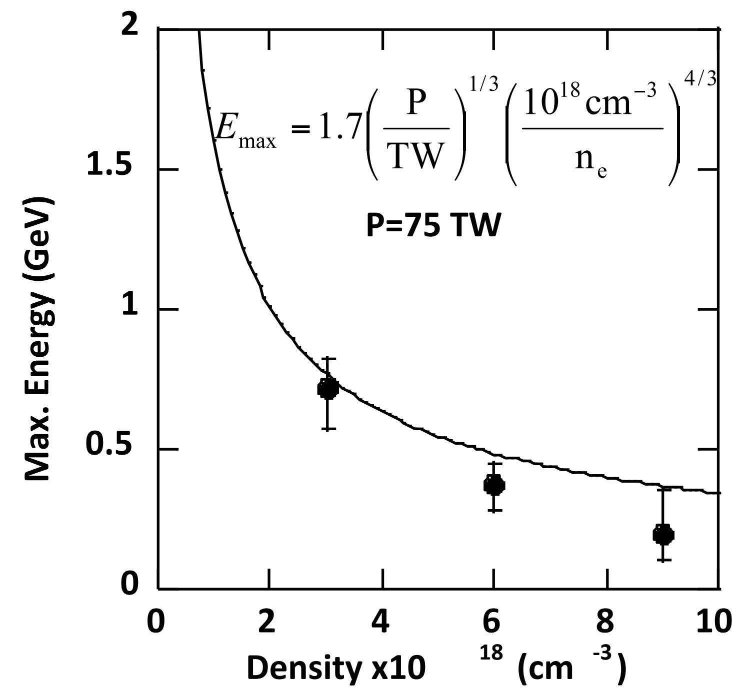
Froula et.al. Phys. Rev. Lett. (2009)

The measured self-injection threshold ($3x10^{18}$ cm^{-3}) limits energy gain to less than 1 GeV

The energy in the electron beams were measured to increase as the electron density was reduced



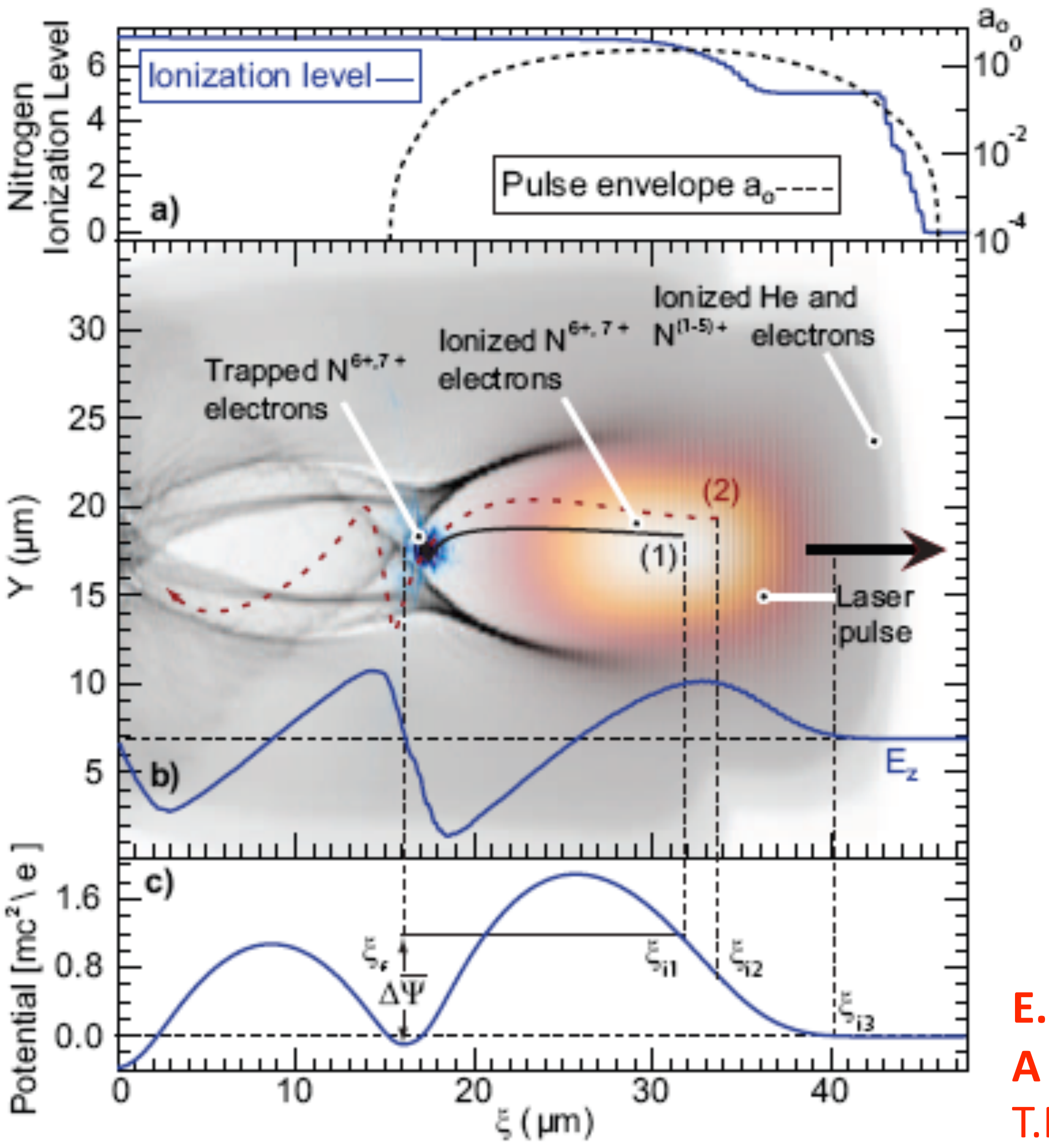
The energy is measured to increase with decreasing density and agrees well with analytical scaling*



*W. Lu PRSTAB (2006)

No electrons were accelerated beyond 100 MeV for densities less than $3x10^{18}$ cm^{-3}

Ionization Induced Trapping in Laser-Produced Wakes



Use trace atoms with a large step in ionization potential

We use 9:1 He : Nitrogen mix.

The two He electrons and the first 5 (L-shell) N electrons form the wake

The 6th (K shell) nitrogen electron is ionized in the wake and trapped more easily by the wake potential than the electrons that support the wake.

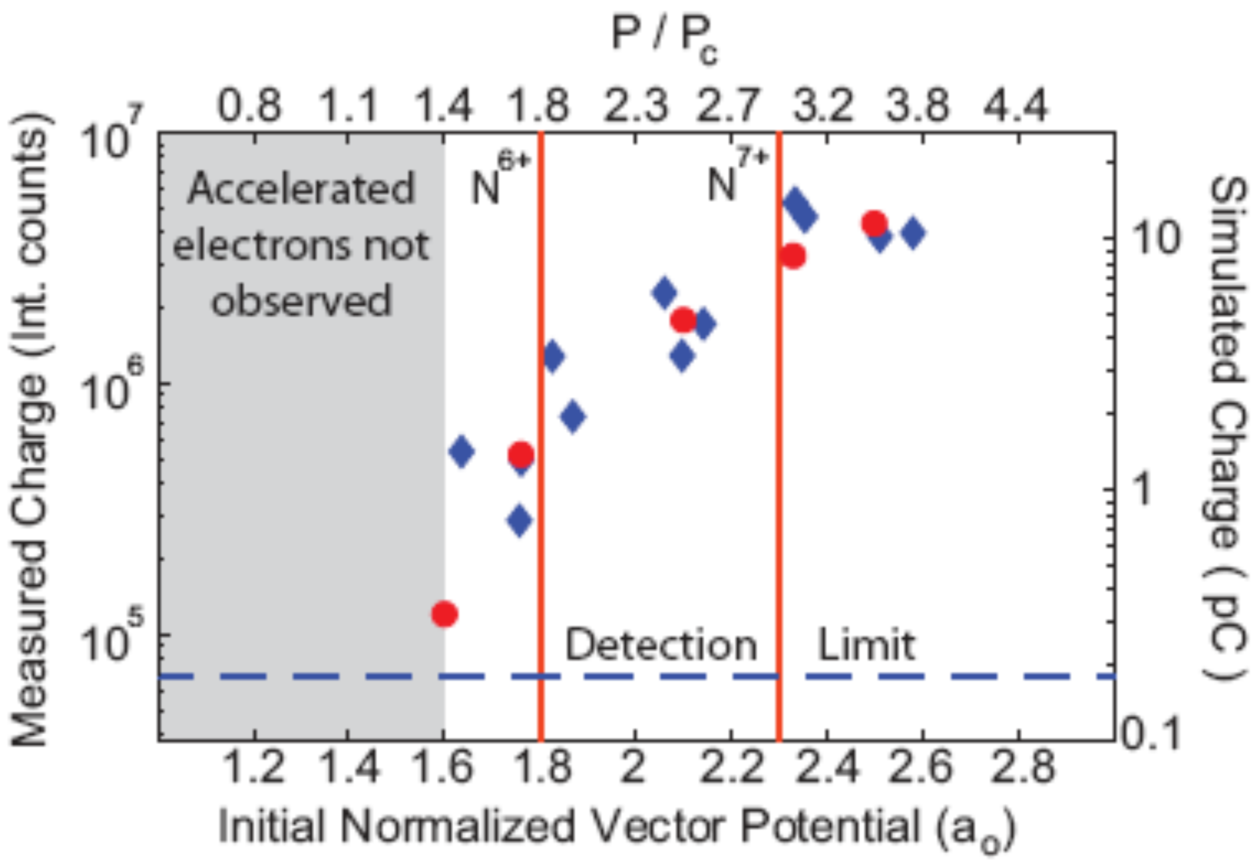
Ionization trapping reduces the wake amplitude and therefore the laser power needed to trap electrons.

E.Oz et al PRL 2007

A . Pak et al submitted Phys Rev Lett (2009)

T.R. Rpwland -Rees et al PRL (2006)

Threshold Behavior Consistent with Ionization Induced Trapping in LWFA



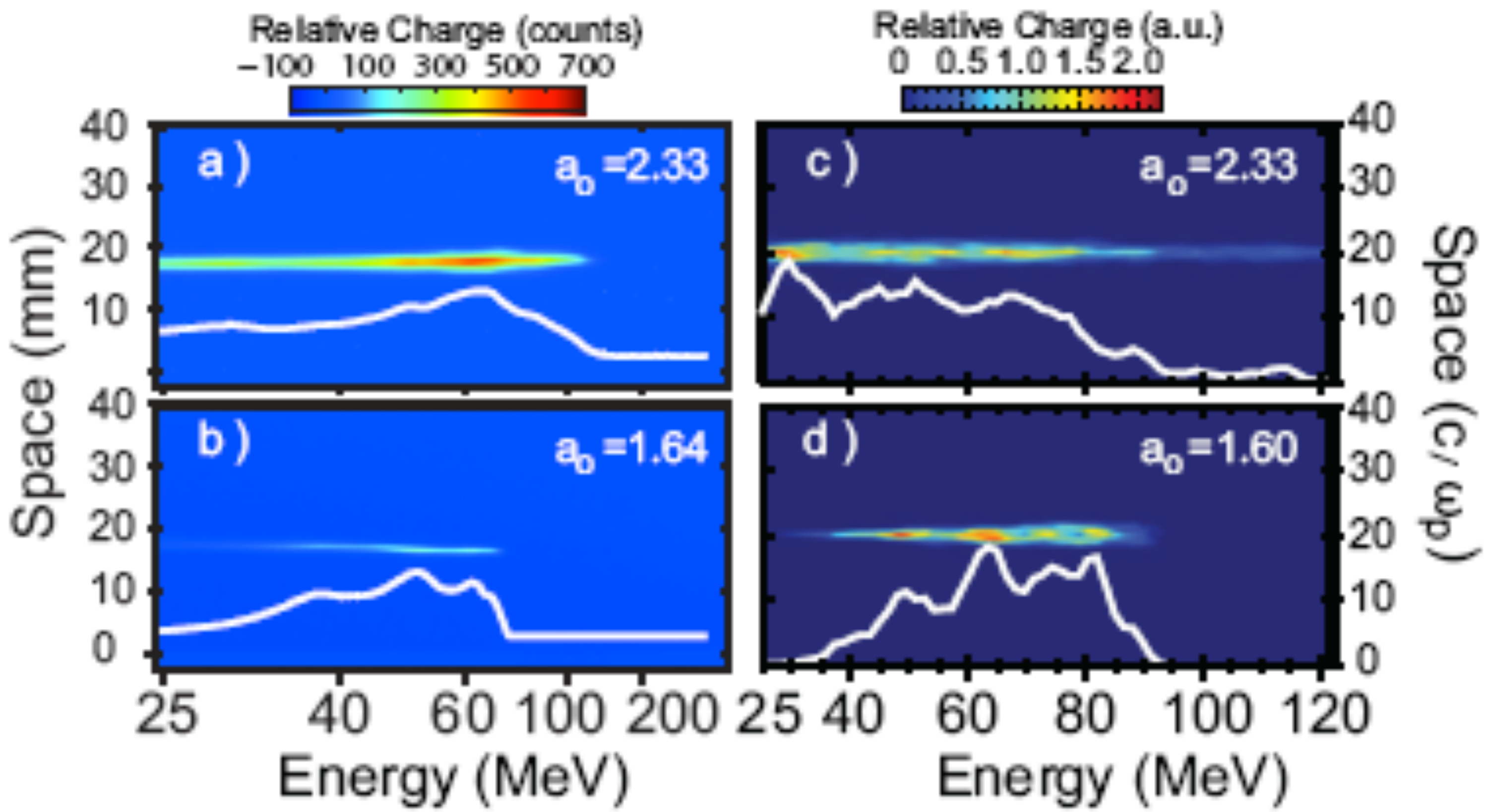
9:1 He:N_2 Plasma

No charge below ao of 2.3 in pure He plasma

A.Pak et al submitted Phys Rev Lett (2009)

Tunnel Ionization of Nitrogen K-shell Electrons into LWFA

Experiment **PIC Simulations**

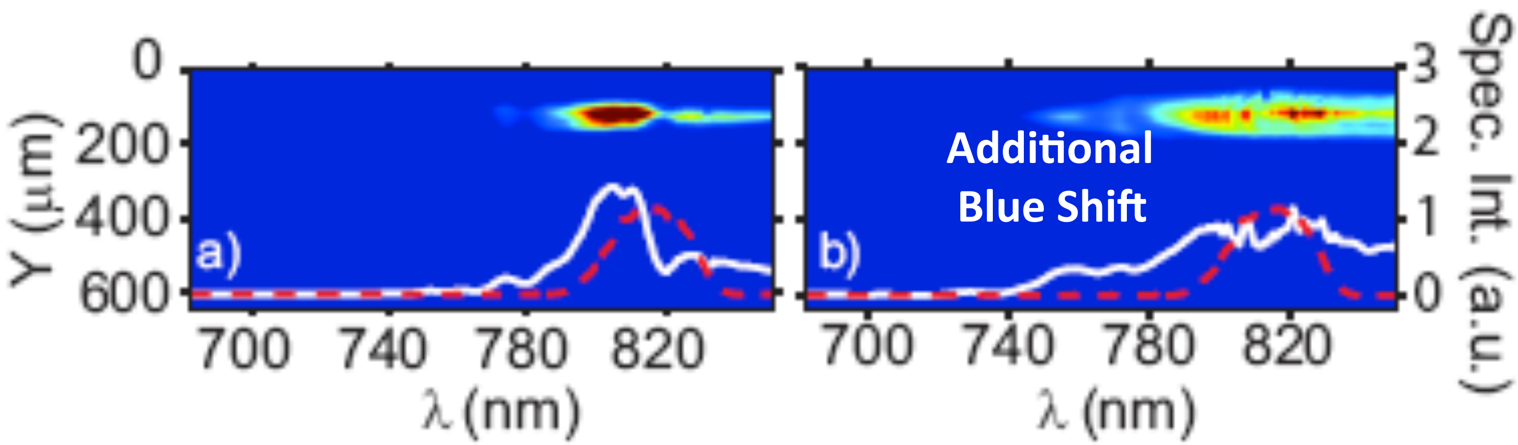


9:1 He:N_2 Plasma

A. Pak et al submitted Phys Rev Lett (2009)

Ionization Trapping Signature in Transmitted Laser Spectrum

A. Pak et al submitted Phys Rev Lett (2009)

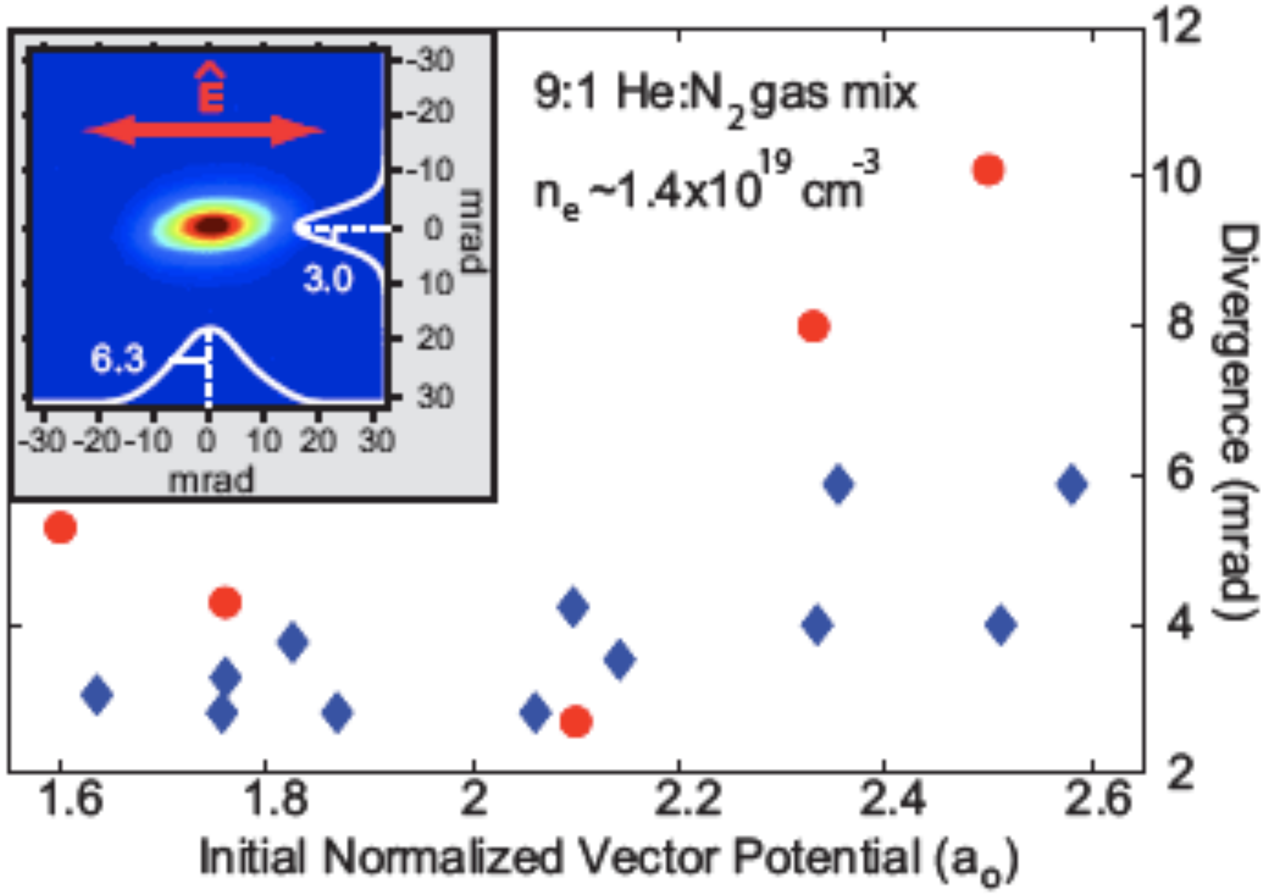


He Plasma

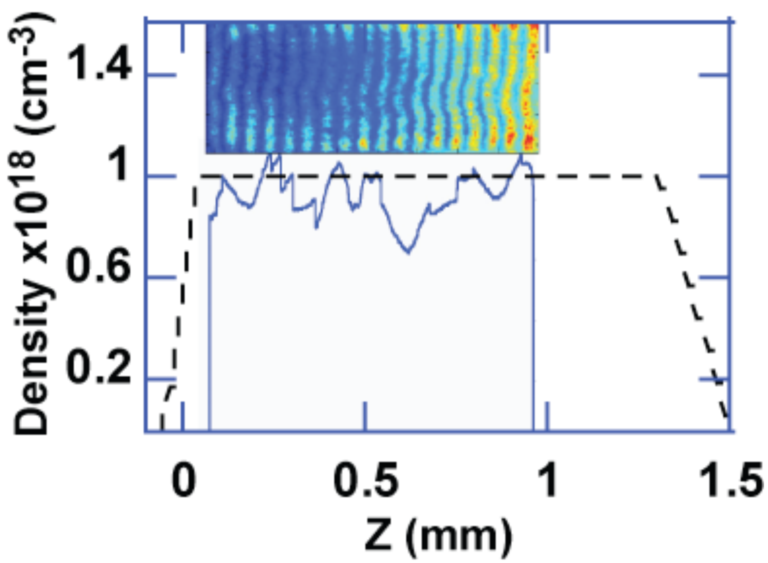
9:1 He:N_2 Plasma

Ionization of the sixth Nitrogen electron inside the wake produces additional blue shift

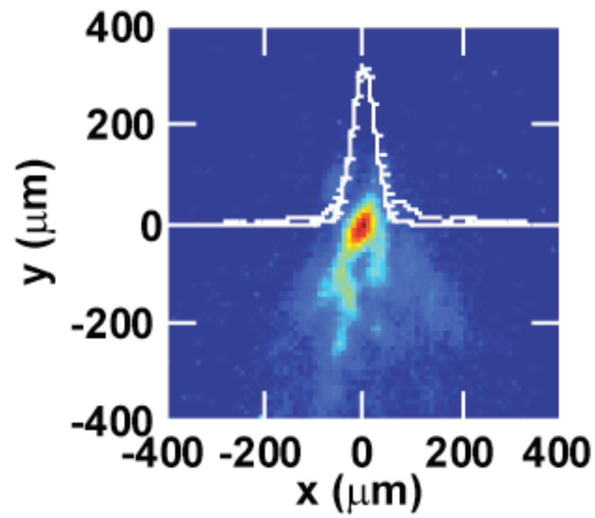
Measurement of Beam Divergence in Plane of Laser Ionization Induced Injection and Trapping



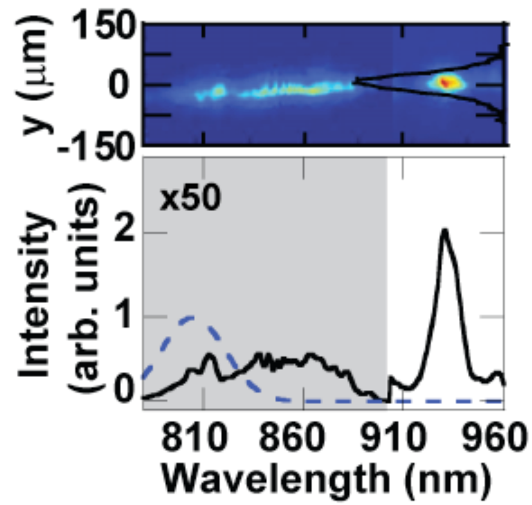
Diagnosis of the Plasma and the Wake in a 1.4 cm Long Gas Cell



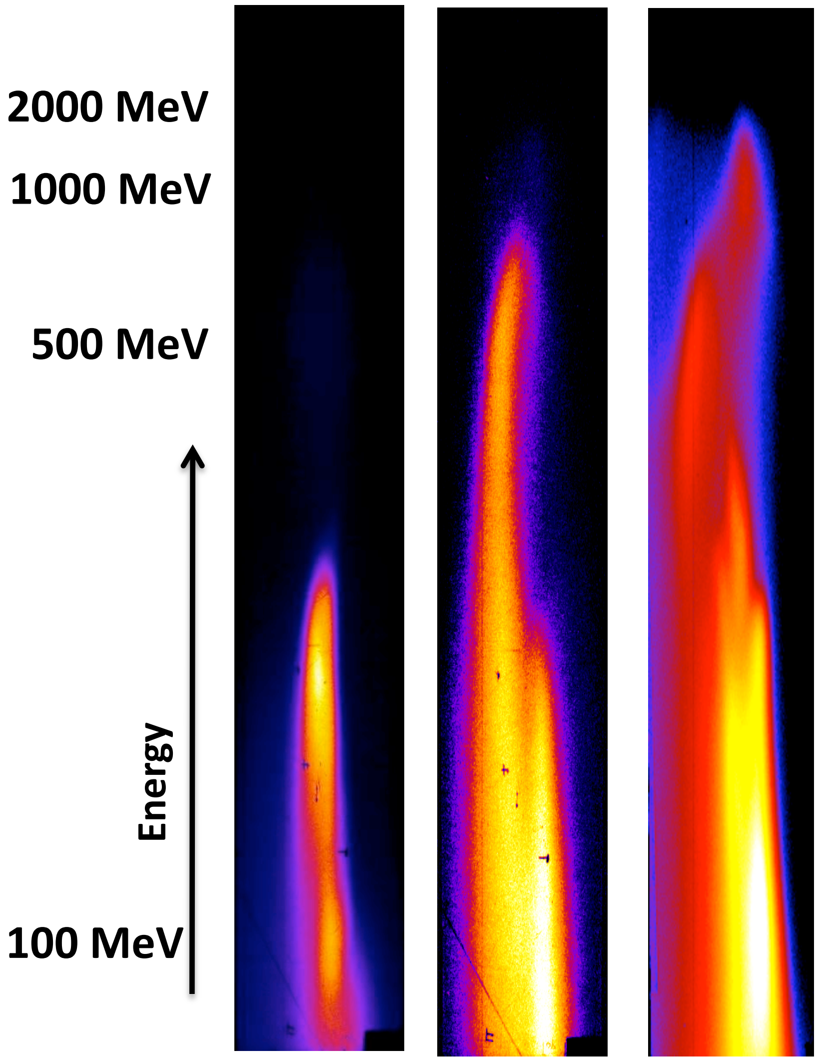
Interferometry



Exit Spot Size and Imaged Spectrum

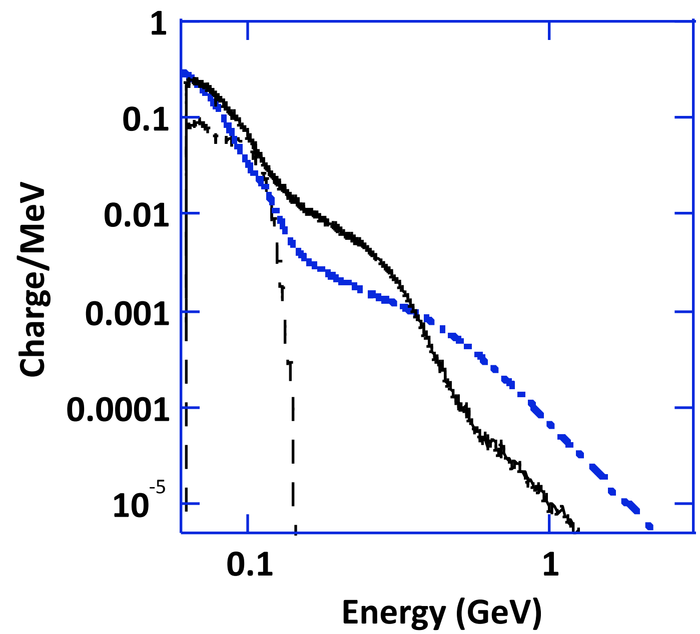


K-Shell Electrons of Oxygen Injected into Wakes



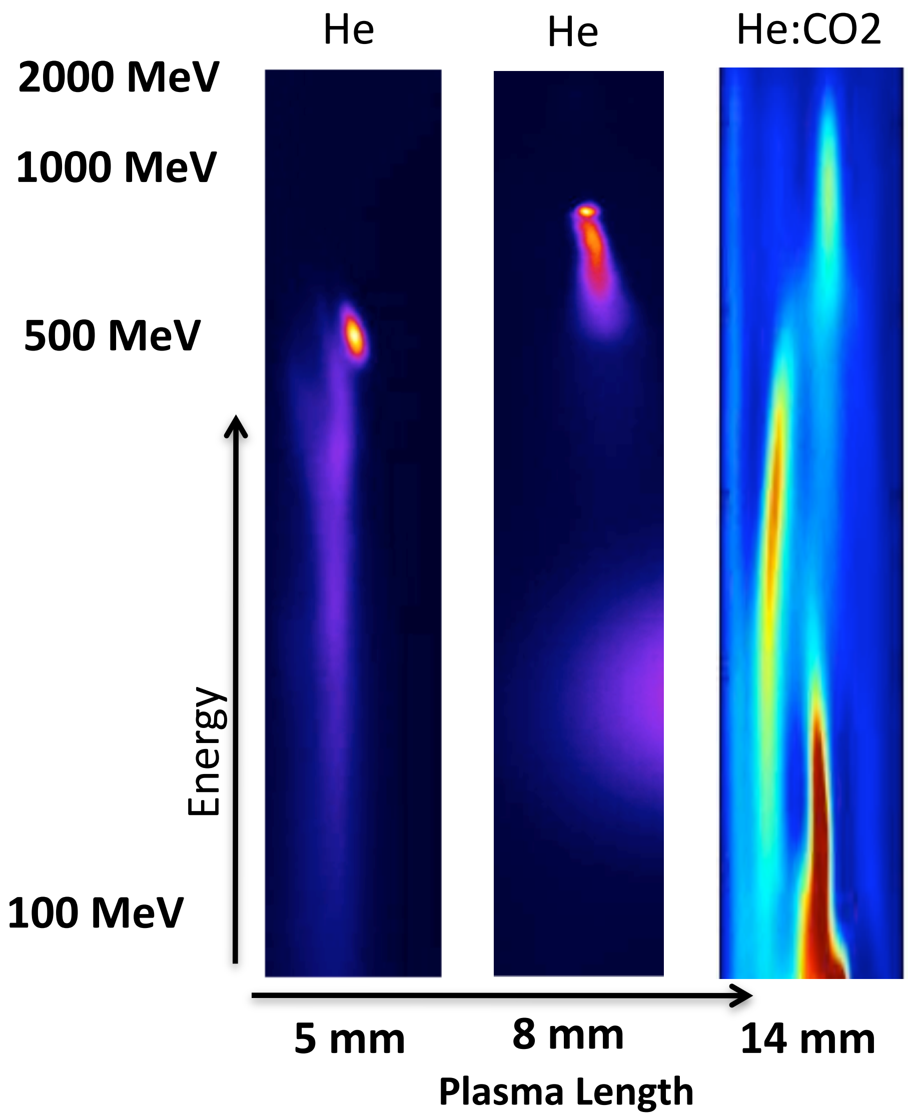
$3x10^{18}$ 50 TW | $1x10^{18}$ 50 TW | $1x10^{18}$ 85 TW

Continuous electron spectra are measured with a 3% CO_2 mixture

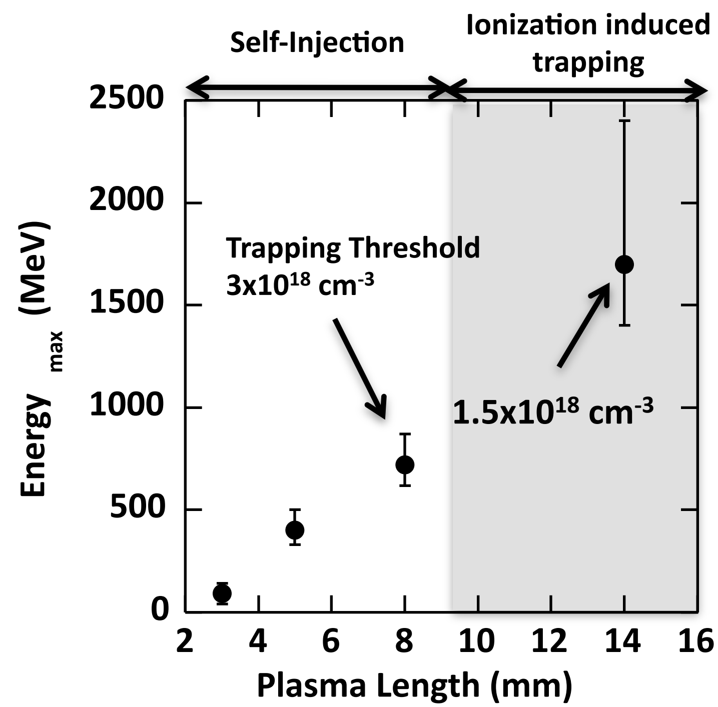


Up tp 2.5 pC of charge above 1 GeV
Maximum Energy 1.7 GV

This collaboration has pushed the limits of energy gain in LWFA while demonstrating the limitations of self-injection



The electron energy is measured as a function of plasma length

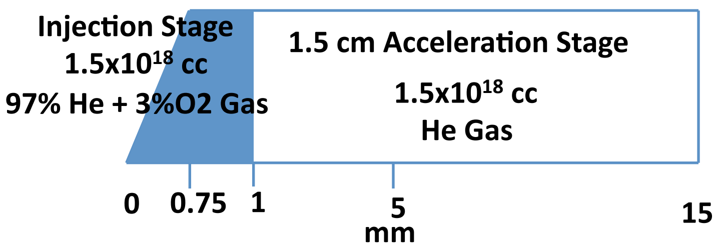


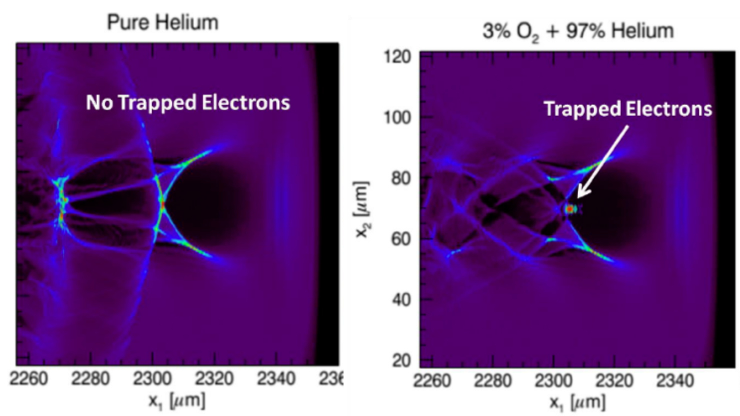
The density is reduced to match the plasma length to the dephasing length

LLNL/UCLA Collaboration : Unpublished data

Two-stage simulations demonstrate monoenergetic 1.5 GeV electron beams using the Callisto laser conditions : 80 TW

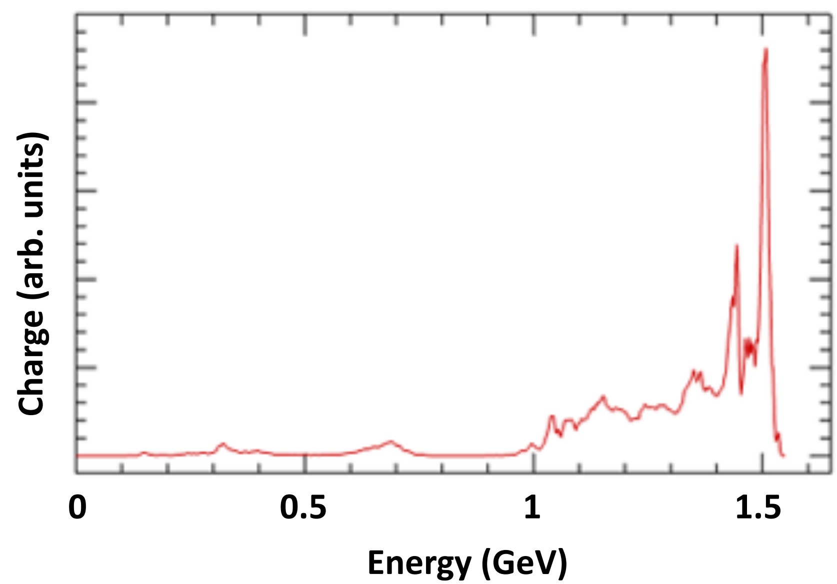
OSIRIS simulations were used to design a two-stage density profile for future Callisto experiments





No self-injection occurs at these conditions; trace amounts of O_2 provide injection

Two-stage injector produces a 1.5 GeV monoenergetic electron beam



Callisto experimental parameters were used in this simulation

LLNL/UCLA Collaboration : Unpublished data

Summary on LWFA

- A matched laser pulse can be self guided
  in a plasma over distances of interest to obtain
  electron energies in the 1+ GeV range.
- Need laser power on the order 100 TW
- Self-trapping may be difficult at densities on the order 1 e 18 cm-3.
- Ionization induced trapping may be a promising way of injecting electrons in low density wakes.

Conclusions

Both beam driven and laser driven Plasma wakefield Acceleration concepts have made remarkable progress.

Robust GeV scale LWFA within grasp with 100 TW laser using self-guided regime.

Expect much effort in controlling injection, beam loading, and emittance in the next few years.

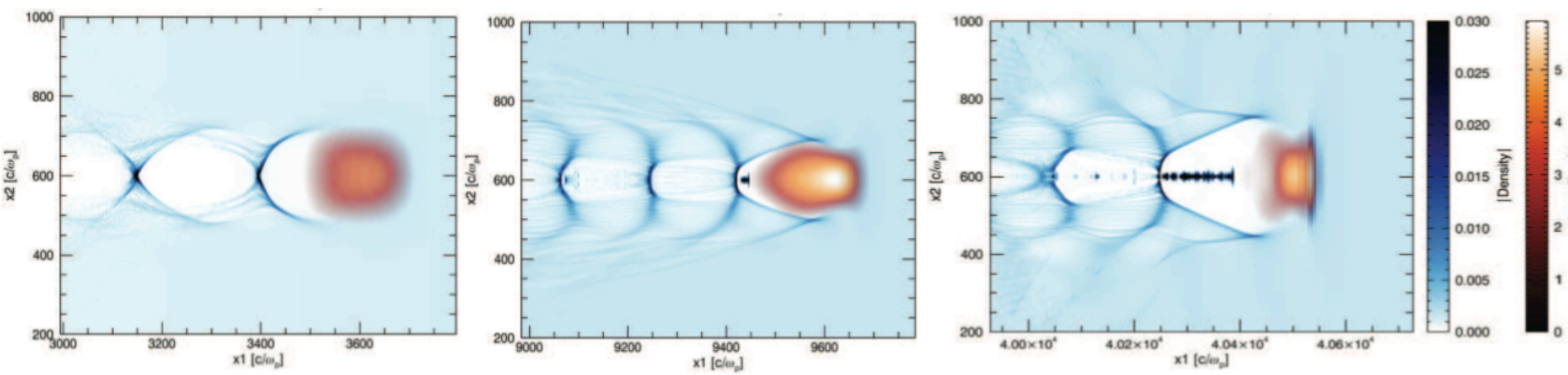
EPILOGUE

John M. Dawson
1930-2001

“This is a story **of Science as a Living Thing** taking
Unexpected turns in directions that were never
foreseen. Science must have goals, but it must
Also have the freedom to follow up interesting
And unexpected results when they turn up.
This is what excites the good young researcher
and it is in their hands that our future rests.”

John Dawson AIP Conf. Proc. 560 p 3 (2000)
Personal Recollections on the Development of
Plasma Accelerators and Light Sources

Particle Simulations of experimental condition show self-guiding, injection and peak energy



- **self-injection occurs after 3 mm of propagation**
- **At the end of the 8.5 mm simulation, a quasi-monoenergetic 760 MeV electron beam is produced**