Laser Based Electron Acceleration

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Outline

- Motivation for R&D work in this area
- Physical aspects : Laser wakefield electron acceleration
- Recent achievements
- At RRCAT : Ultra-intense laser-plasma interaction
  - *Laser driven electron acceleration*
- Conclusion

Why Interest in Laser Driven Accelerators ?

❖ Possibility of making big accelerators as very compact and much cheaper devices

- Energy source : RF cavity
- Electric field < 50 MV/m
- Large accelerators (several km size) for TeV energy
- For compact accelerators (few m) : E ~ 100 GV/m

❖ Facilitate table-top synchrotron radiation sources

(Nature Physics, 9th December 2007 issue)

❖ Boost applications in industrial / medical and other fields

- 20 – 50 MeV energy electron beam : Radiotherapy / Radiography

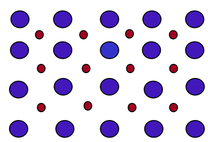
(Plasma Phys. & Controlled Fusion, November 2005)

Laser Beams: Compact Particle Accelerators

- Laser : Ability to deliver high peak power over small area
- High electric fields (≥ 100 GV/m) are available with intense laser beams, but being transverse, they can not be effective for acceleration
- For the above high fields, accelerating structure would breakdown and get ionized
- Plasma : Ionized medium
- **Look for production of high longitudinal electric fields**

Plasma : Medium for Electron Acceleration

- Electron-plasma wave (Longitudinal mode)



$$\omega_p = \sqrt{4\pi n_e e^2/m}$$

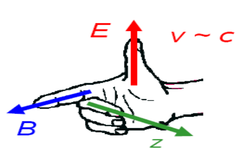
$$E(V/m) = 96\sqrt{n_e (cm^{-3})}$$

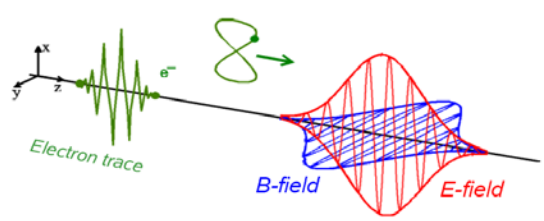
For $n_e = 10^{18}\ cm^{-3}$	$E \sim 100\ GV/m$	$\lambda_p = 2\pi c/\omega_p \approx 30\,\mu m$

- Ultrashort high intensity laser pulses can excite electron plasma wave of such amplitudes through ponderomotive force

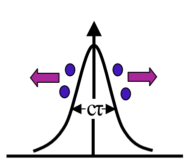
Electron Dynamics in Intense Laser Pulse

$$F = e[\ E + v \times B\ ]$$



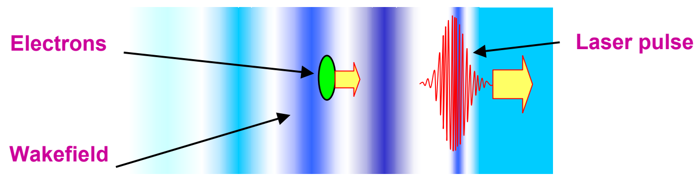


$$F_{NL} \propto -\nabla I_L$$



- Ultrashort high intensity laser pulses have very sharp intensity gradient in the direction of propagation
- This exerts huge ponderomotive force in the longitudinal direction, exciting large amplitude electron plasma wave

Laser Wakefield Electron Acceleration



Phase velocity of the laser wakefield is equal to group velocity of the laser pulse (~ c)

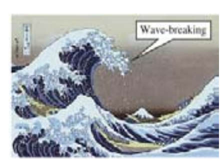
- Electrons of velocity ~ V_{ph} will get accelerated
- A very slight increase in velocity of relativistic electrons will increase their energy by a large amount

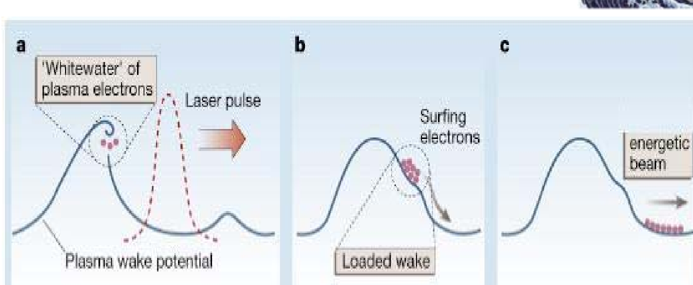
Injection of Relativistic Electrons

External injection: Very tedious : Synchronization (fs,um)

Self-injection in plasma :"Wave breaking"

Wave breaking occurs when the field amplitude of the wave increases such that the particles excursion becomes comparable to the plasma wavelength.



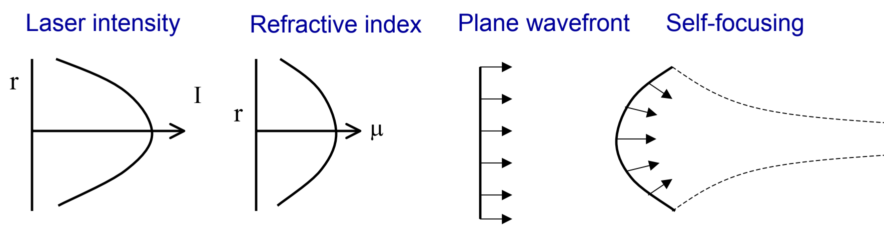


Broad energy spectrum and shot to shot fluctuation :

Uncertain location of injected electrons at different times

Relativistic Self-Focusing

$$\mu = (1 - 4 \pi n_e e^2 / m \omega^2)^{1/2}$$

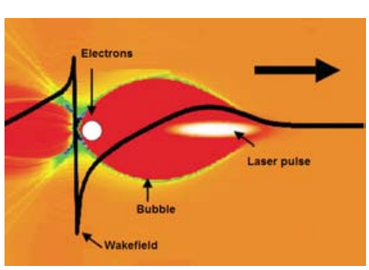


For self focusing: $P > P_{cr}$ (Critical power) : P_{cr} (GW) = $17.4\ n_c/n_e$

For $\lambda_L = 795$ nm (Ti: sa), $n_e = 10^{19}\ cm^{-3}$ ⇒ $P_{cr} \approx 3$ TW

Wake Field Acceleration : Bubble Regime

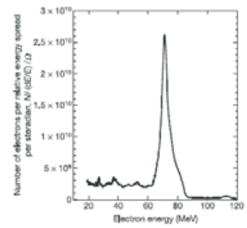
- Ultra-relativistic intensities ~ 10^{19} -10^{20} W/cm^2
- Pulse length ($c\tau$) < Plasma wavelength (λ_p)
- Huge ponderomotive force of the laser pulse blows out electrons forming a void (bubble)
- Significant number of electrons are trapped at the stem of the bubble and get accelerated



Highly mono-energetic and directional electron beam of 100's of MeV

Pukhov & Meyer-ter-Vehn
Appl. Phys. B 74, 355 (2002)

LWFA : Major Milestone



Mono-energetic beam spectrum measured by S P D Mangles et al

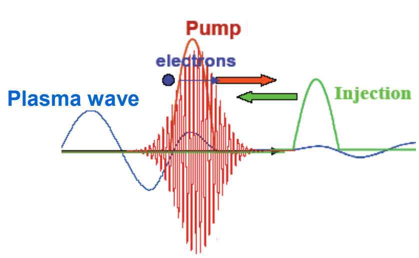
- **Bubble regime : Self trapped electrons as a single group**
- **Monoenergetic beam : Energy spread ~ 10%**

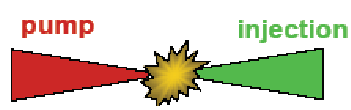
- **But shot-to-shot variation in electron beam energy**
- **Poor control on self injected electrons**
  (Wave breaking: Highly nonlinear process)

Energy Control and Stability: External Injection Using Another Laser Pulse

LOA, Ecole Polytechnique, France

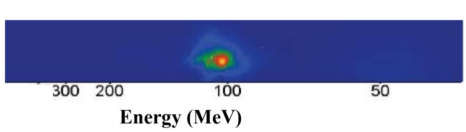
Counter-propagating geometry:





Electron beam energy can also be changed by shifting the location of collision point.

❖ **100 % reproducibility**

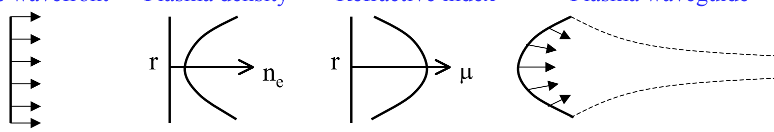


J. Faure et al., Nature 444, 737, Dec 2006

Way to Laser Based Multi-GeV Acceleration

- Rayleigh range of the focused laser beam (sub-mm)
- The interaction length may be increased by using a preformed plasma channel to focus the laser beam

$$\mu = (1 - 4 \pi n e^2 / m \omega^2)^{1/2}$$

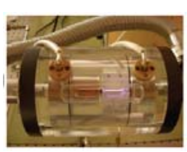


- Capillary discharge plasma of several cm length
- Higher power lasers required to compensate for pump depletion

Gev Electron Beam from a Laser Wakefield Accelerator

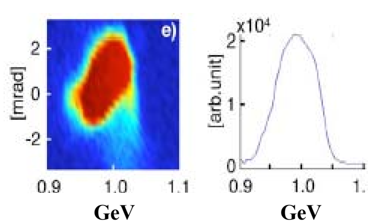
Capillary Discharge Plasma Channel as Wave guide

LBNL, Berkeley, USA



40 TW, 35 fs Ti: sapphire laser

3.3 cm long gas filled capillary column



E ~ 1 GeV

Q ~ 50-100 pC

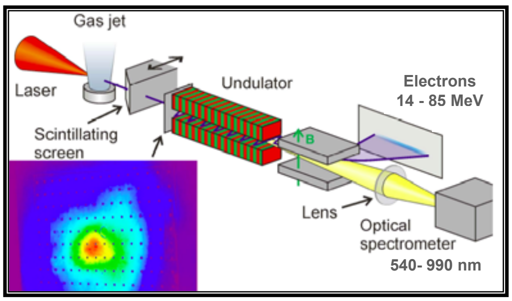
Leemans et al., Nature Physics, 2, 696 (2006)

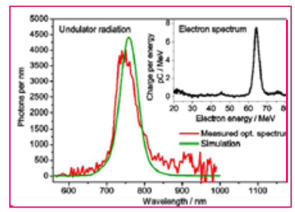
Undulator Radiation from Laser-Accelerated Electron Beam

IOQ, JENA, Germany and University of Strathclyde, UK

Laser : 5 TW, 85 fs Ti: sapphire, 5 x 10^{18} W/cm^2, n_e = 2 x 10^{19} cm^{-3}

Undulator : 2 cm period, 50 periods, 10 mm pole gap, B_{max} = 0.33 T

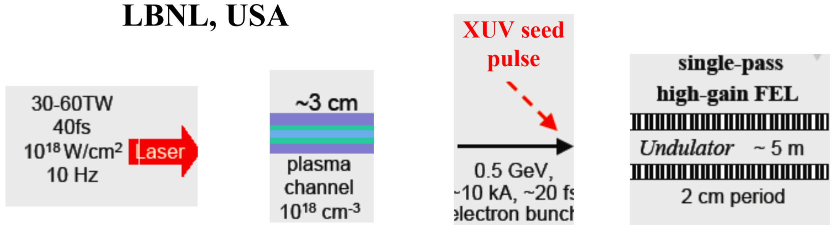




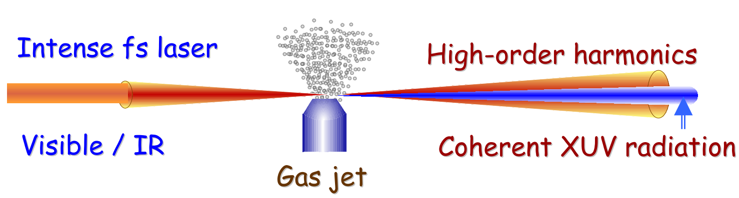
Nature Physics, 9th Dec 2007

Laser Wakefield Acceleration Driven High Gain FEL Amplifier Project

LBNL, USA



XUV seed pulse : High harmonic generation



Femtosecond PW lasers for laser-plasma accelerator

ASTRA GEMINI, RAL, UK

2x 0.5 PW, 30fs
Rep. 20 sec per shot

(Autumn 2007)
(Capillary accelerator experiment will be carried out by Euro group)

fs PW, SIOM, China

0.9 PW, 29fs
Rep. 20 min per shot

(Jan. 2008)
(The world highest power fs laser is available for acceleration experiment)

Plasma Wakefield Acceleration

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

(Nature Letters 15 Feb 2007)

Stanford Linear Accelerator Centre

- 42 GeV electron beam from 3 km long SLAC accelerator
- Plasma wakefield ~ 52 GV/m
- Acceleration length = 85 cm
- Energy gain = 42 GeV

Laser Wakefield Electron Acceleration Studies at RRCAT

(in collaboration with KEK, Japan)

- Experiments at $n_e \sim 10^{19} - 10^{20}$ cm^{-3}. For this density range, critical power for self focusing will be 0.3 - 3 TW. Our laser power of 10TW is well above this threshold. So relativistic self guiding

- For laser pulse ~45 fs : Sm-LWFA

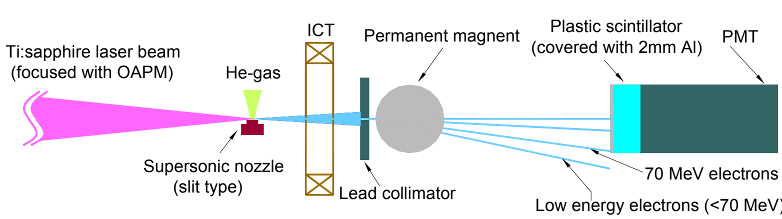
- For $I \sim 10^{18}$ W/cm^2 used in the experiments and $n_e = 10^{19} - 10^{20}$ cm^{-3}, the electric field would be ~ 60 GV/m - 3 TV/m .

Naik & Gupta, International Journal of Modern Physics B 21, 459 (2007)

Experimental Set-up

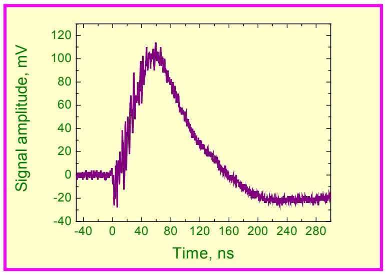
Laser Parameters

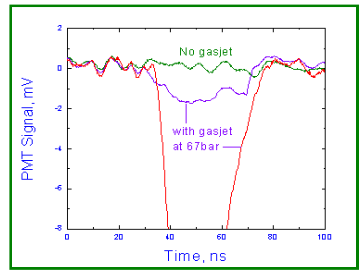
Pulse power	: 10 TW
Pulse duration	: 45 fs
Pulse energy	: 450 mJ
Pulse repetition rate	: 10 Hz
Focal spot radius	: 10 μm
Intensity ($W\ cm^{-2}$)	: 2×10^{18}



Experimental results

- Laser and gas-jet interaction parameters optimized

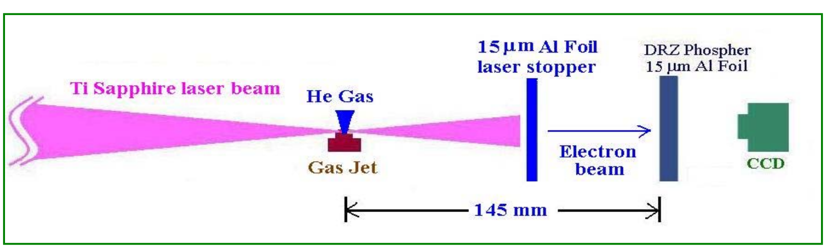


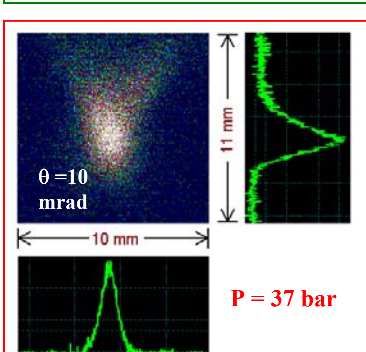


- Electron energy > 70 MeV is consistent with expected wakefield and dephasing length.

B.S. Rao et al., International Workshop on "Laser and Plasma Accelerators-2007," Azores, Portugal, August 2007.

Electron beam profile at low pressure





Gas pressure : **37 bar**

Gas jet -phosphor : 145 mm

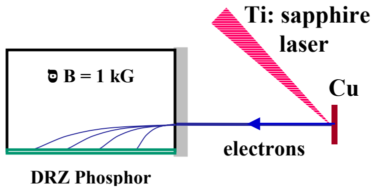
Collimated beam of electrons

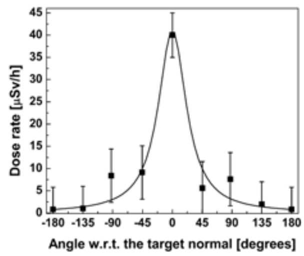
Low divergence ~ 10 mrad

Fluctuation in beam direction ~ 10 mrad

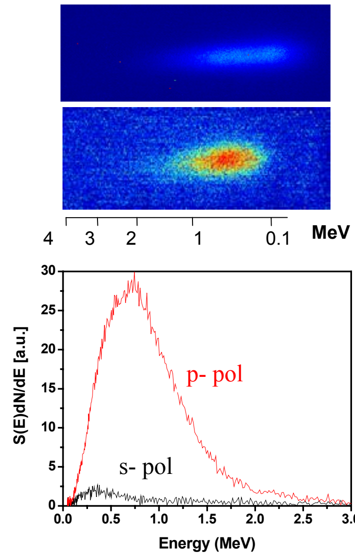
Fast Electrons Produced from Solid Targets

- Laser Intensity ≈ 1.3 x 10^{18} W/cm^2, $\tau \approx 45$ fs

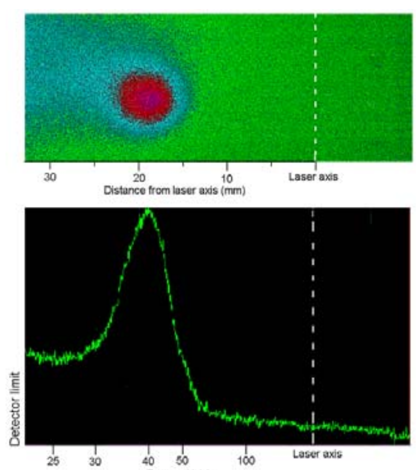




J. Appl. Phys. 102, 63307 (2007)



Electron Energy Spectrum From Gas Jet

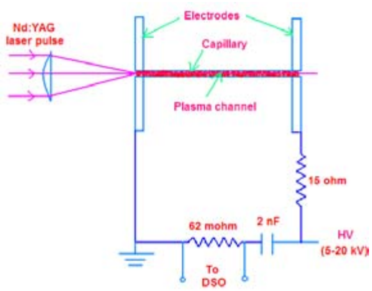


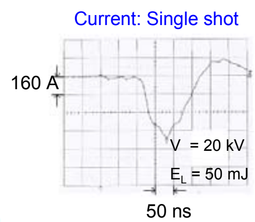
Peak energy ~ 40 MeV

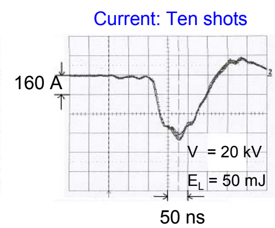
ΔE/E ~ 0.3

❖ **Experiments are continuing to achieve higher energies and higher monochromaticity.**

Laser-Triggered Capillary Discharge Plasma





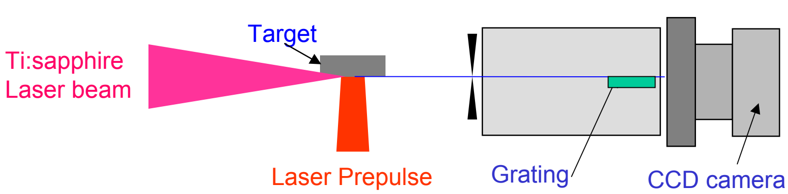


Plexi glass capillary
Length : 70mm,
Diameter : 500µm

Peak discharge current	:	~ 500 A,
Time of peak current	:	~ 180-190 ns
Jitter	:	< 10 ns

- **Experiments to test optical guiding of high intensity laser pulses and electron acceleration are underway.**

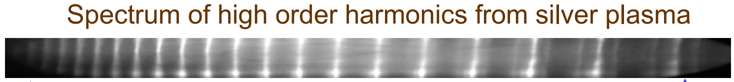
High Order Harmonic Generation from Low Excited Plasma



Optimisation of laser and plasma parameters

J Opt Soc Am 23, 2535 (2006)

Spectrum of high order harmonics from silver plasma



61st

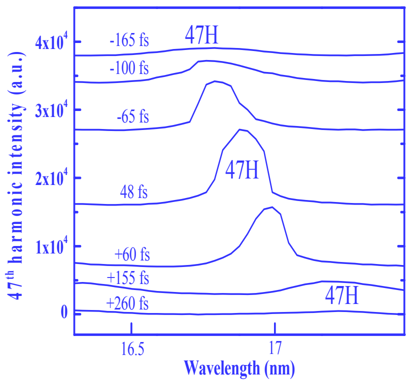
Appl. Phys B 87, 243 (2007)

21st

Coherent soft x-ray radiation is produced at several discrete wavelengths down to 12.9 nm

Tuning of Harmonic Frequencies

Effect of Chirp Variation



Negatively Chirped Pulse

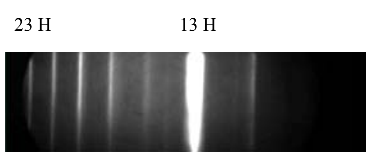
Positively Chirped Pulse

Harmonic tuning range up to 0.8 nm

Appl. Physics B 87, 243 (2007)

Intensity Enhancement through Harmonic Tuning

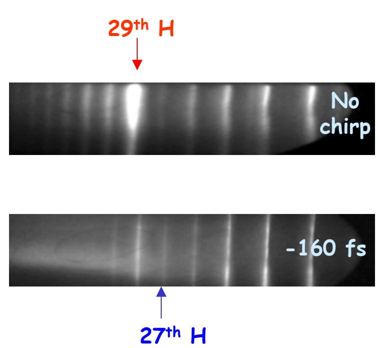
Indium Plasma Harmonics



13th harmonic: 200 X

Phys. Rev. A 74, 63824 (2006)

Chromium Plasma Harmonics



In II $4d^9 5s^2 5d\ ^1S_0 - 4d^9 5s^2 5p\ ^1P_1$

is close to 13th harmonic

Optics Letters 32, 65, 2007

Conclusion

- ❖ Presented some physical aspects involved in laser wakefield electron acceleration and an overview of recent achievements world wide.

- ❖ Described our experiments on laser based electron acceleration at RRCAT and presented some initial results. Studies are continuing to achieve stable and monoenergetic electron beam and to set up capillary plasma wave guides for ultraintense laser pulses.

- ❖ Plan to upgrade Ti:sapphire laser to 150 TW to perform studies in ultrahigh intensity relativistic laser-plasma interaction.

  - LWFA with capillary discharge plasma waveguide
  - X-ray lasing, high order harmonic generation and amplification
  - Generation of high energy proton / ion beam, neutrons, γ-rays and their applications

Participants

From RRCAT India : P.D. Gupta, P.A. Naik, J. Chakera, A. Moorti, S.R. Kumbhare, P.K. Tripathi, V. Arora, H. Singhal, B.S.Rao, U.Chakravarty, A. Upadhyay, R.A. Khan, R.K. Bhat, R.P. Kushwaha, and S. Sebastin

From KEK Japan : K. Nakajima, and T. Kameshima

Acknowledgements

- ❖ Shri C. P. Navathe and colleagues for electronics support.
- ❖ R. Ganeev for HHG collaboration
- ❖ Dr. K. Patel for PIC PSI-3D code.
- ❖ Dr. V. C. Sahni and Prof S Kurokawa for their keen interest

Welcome to visit our laser labs

Thank You !

PICPSI-3D (Particle-in-Cell Plasma Simulation -3D)

- Interaction of relativistic laser pulse with preformed plasma in 3D
- Evolution of laser pulse and collisionless plasma is studied by solving equation of motion for particles & Maxwell's equations for fields.
- Code written by Dr. K. Patel (L&PTD, BARC) and suitably modified for laser-plasma acceleration studies. Dedicated server commissioned in our laboratory.
- Code has been run for Laser : a_0=5, λ = 0.8 μm, focal spot ~ 5λ, τ_L~ 2λ, plasma λp~12λ. Clear Bubble is visible after ~ 185μm travel of laser pulse inside plasma. From 185μm → 200 μm, electrons launched and accelerated inside bubble.