Laser Plasma Electron Accelerator: Experimental studies performed at RRCAT, Indore

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&

“Workshop and Conference on Laser Plasma Accelerator ”

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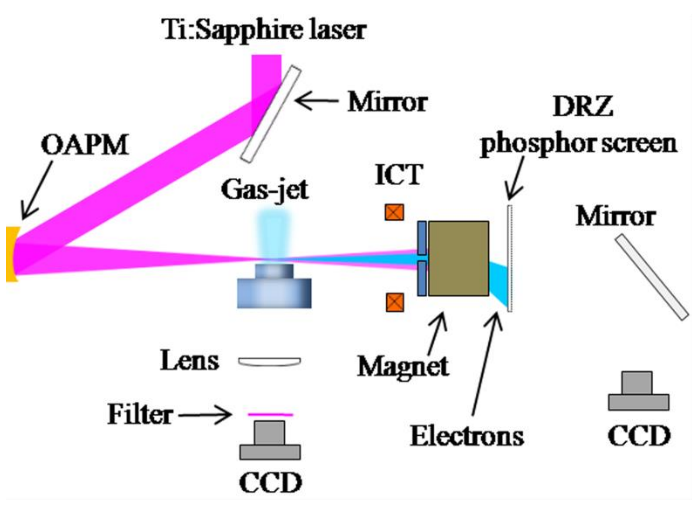
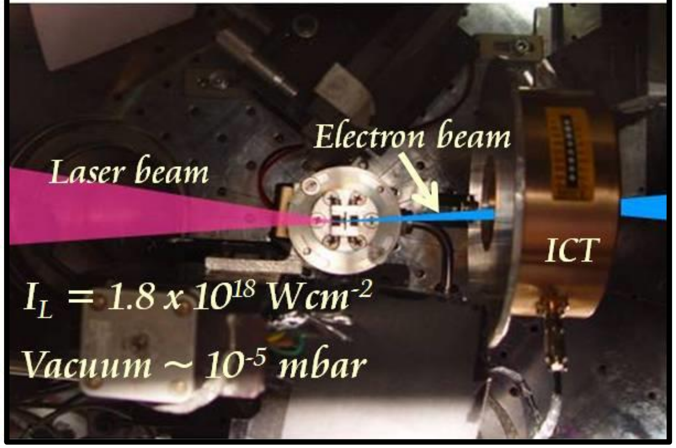
International Centre for Theoretical Sciences (ICTS)– TIFR, Bangalore

LWFA Experiments with 10 TW Laser

Schematic of the experiment



Top-view of the setup



Laser Parameters

Pulse duration	45 fs
Pulse energy	400 mJ
Pulse repetition rate	10 Hz
Pulse power	10 TW
Focal spot (FWHM)	18 - 11 μm
(OAP focal length = 40, 30 and 27 cms)	
Intensity (W cm^{-2})	>10^{18} W/cm^2

New J. Phys. 12, 045011 (2010)

Phys. of Plasmas 18, 093104 (2011)

Phys. Rev. Spec. Topics Acc. Beams, 16, 091301 (2013)

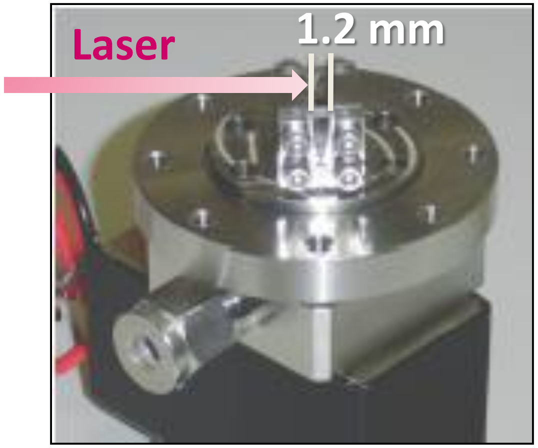
Appl. Phys. Lett. 102, 231108 (2013)

Phys. Rev. Spec. Topics Acc. Beams 17, 011301 (2014)

Appl. Phys. B 120, 149 (2015)

Plasma Physics and Controlled Fusion Under Review (2017)

Gas Jet Parameters

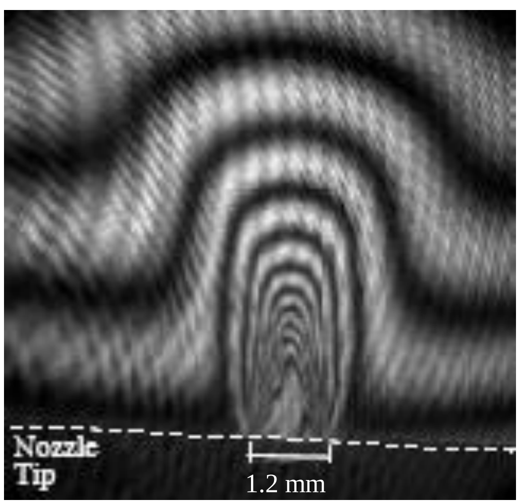


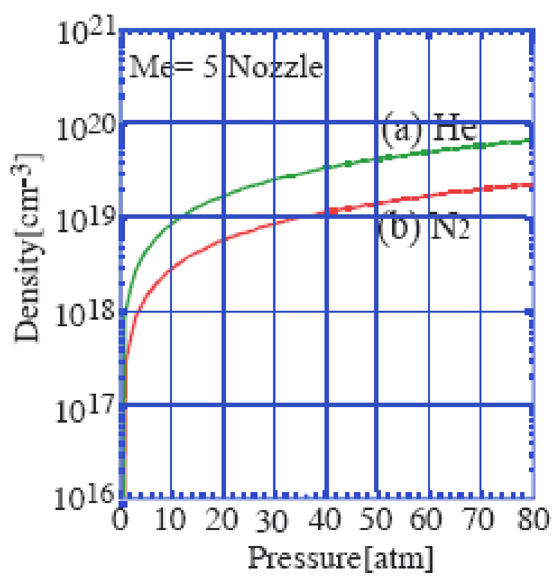
(Smart Shell Co., Japan)

Gas jet Parameters

Nozzle Type	supersonic nozzle shock-wave free
Nozzle Dimensions	1.2 mm ×10 mm
Gas:	He
Gas Pressure	35-75 bar
Electron Density	5-9.5 × 10^{19}/cc

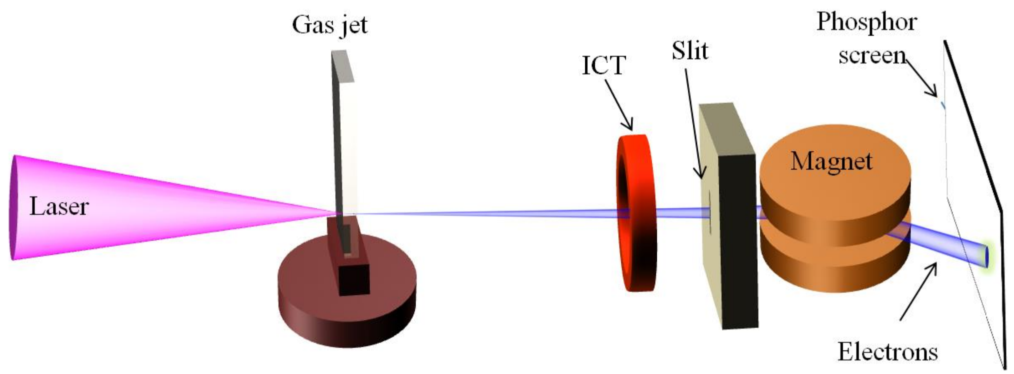
Laser beam focused along 1.2 mm jet length

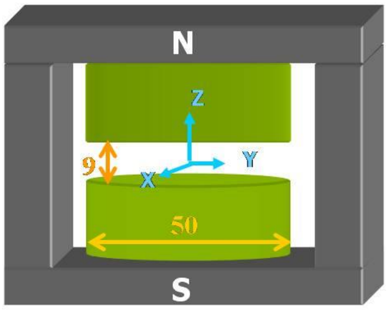


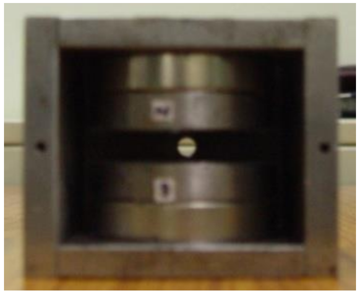


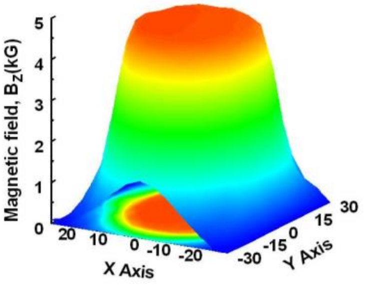
Electron Energy Measurement

Magnetic spectrograph with a permanent magnet :









Circular field profile

D_{eff} ~ 50mm

Pole Gap ~9mm

B_{max} ~ 4.6 kG

Electron Beam Charge Measurement

Integrating Current Transformer

Bergoz ICT-082-20:1

Sensitivity : 2.51 V- s / C

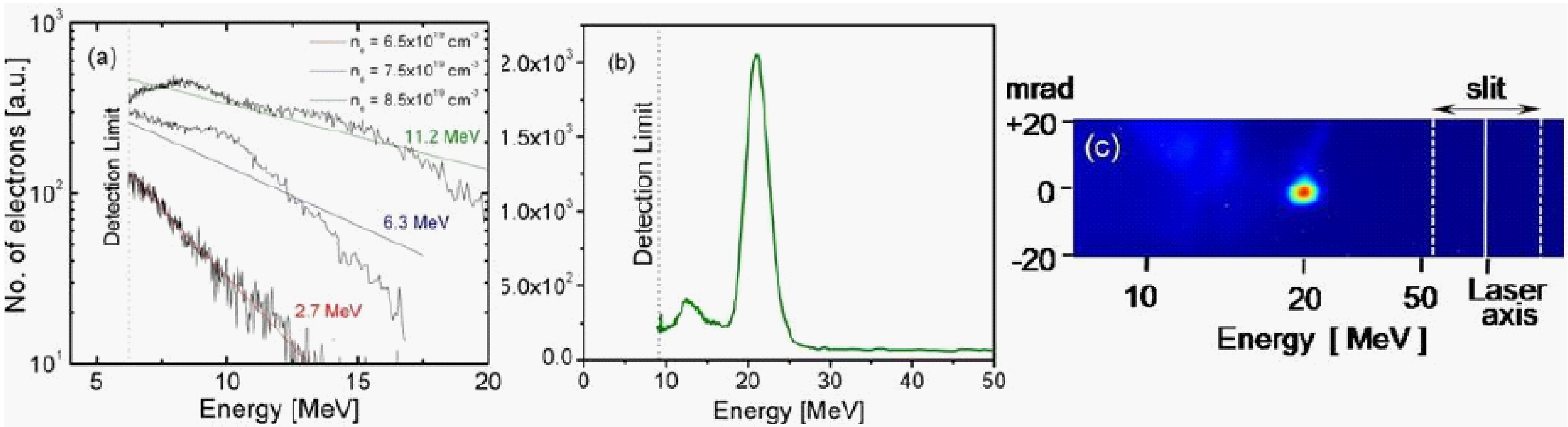
Absolute calibration data for DRZ Phosphor Screen

Absolute calibration for DRZ high: ~7.82 $\pm$ 0.56 x 10^9 photons/sr/pC

Y. C. Wu et al., Rev. Sci. Intsrum. 83, 026101, 2013.

LWFA: With large focal spot

(With OAPM of f=40 cm, Focal spot ≈18μm FWHM, I ~ 10^{18} W/cm^2)



Mono-energetic beam at n_e ~8.5 x 10^{19} cm^{-3}
at I ~10^{18} W/cm^2 in ~20% of the laser shots

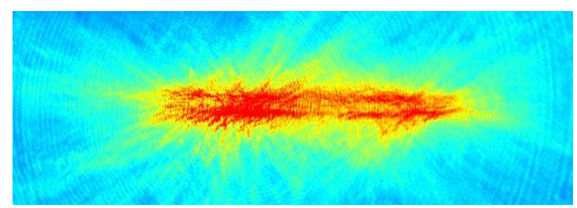
Divergence (θ) : ~ 4 – 7 mrad

Peak energy (E) : ~ 10 – 20 MeV

Energy spread (ΔE/E) : ~ 4 – 8 %

Beam charge (Q_{mono}) : ~ 10 – 60 pC

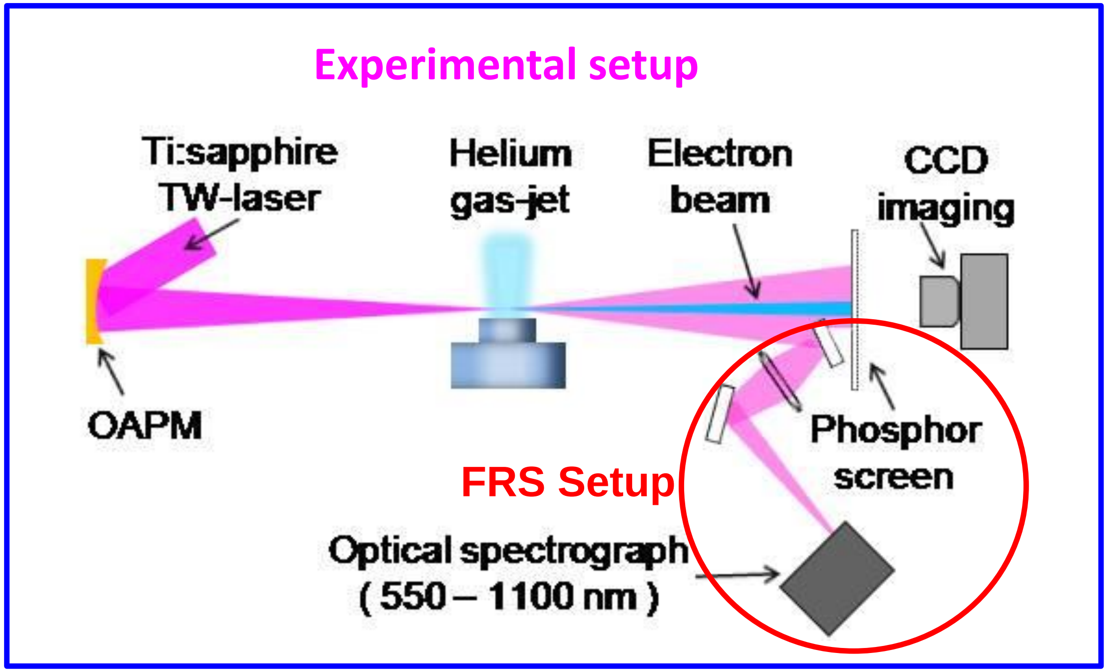
Laser filamentation

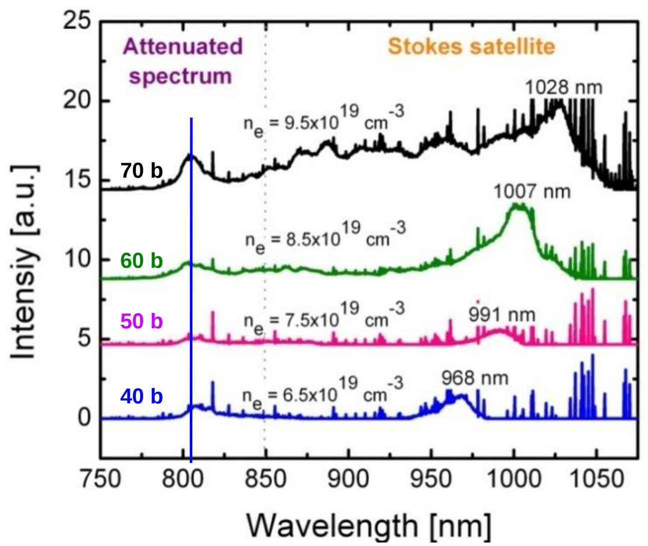


Maximum length of the channel is ~ 400 μm.

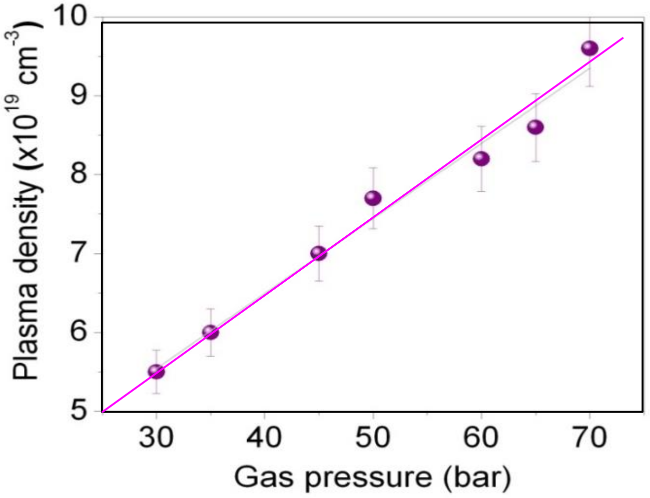
New J. Phys. 12, 045011 (2010)

Forward Raman Scattering



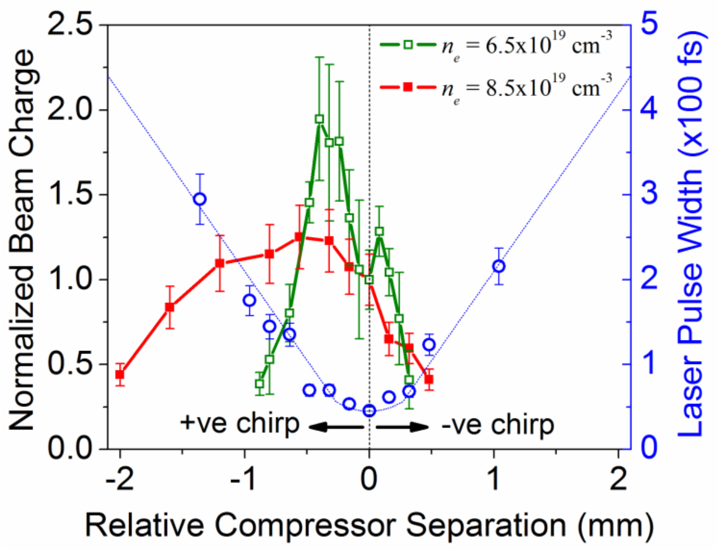


- ✓ FRS instability drives large amplitude plasma waves.
- ✓ The growth rate of the plasma waves depends on the plasma density .
- ✓ The wavelength of the Raman shifted e.m. wave depends on the plasma density.
- ✓ The measurements provide *in situ* plasma density



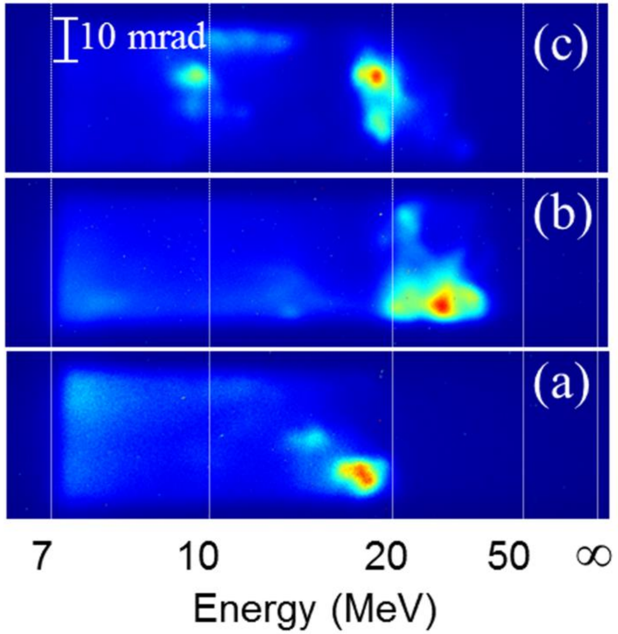
LWFA: Effect of laser pulse chirp

Variation in Total Charge:



Variation in the integrated electron beam charge with compressor grating pair separation (chirp) measured w.r.t. the "zero" setting (separation corresponding to minimum pulse duration). The total charge for "zero" setting of the compressor is 2 nC and 8 nC respectively for plasma density 6.5×10^{19} cm^{-3} and 8.5×10^{19} cm^{-3}. The variation of the laser pulse width (circles) with grating separation is also shown.

Effect of laser pulse chirp: Quasi-monoenergetic electron beam energy



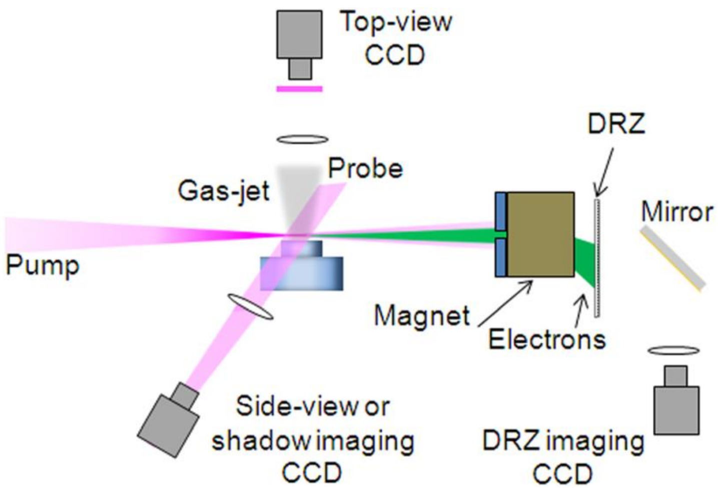
Images of quasi-monoenergetic electron spectra recorded at $n_e \simeq 8.5 \pm 0.5 \times 10^{19}\ cm^{-3}$, for different separations of the laser pulse compressor gratings : a) 0 μm (45 fs), b) -320 μm (70 fs), and c) -640 μm (135 fs).

Phys. Rev. ST-Accel. Beams, 16, 091301, 2013.

Electron acceleration at higher intensity

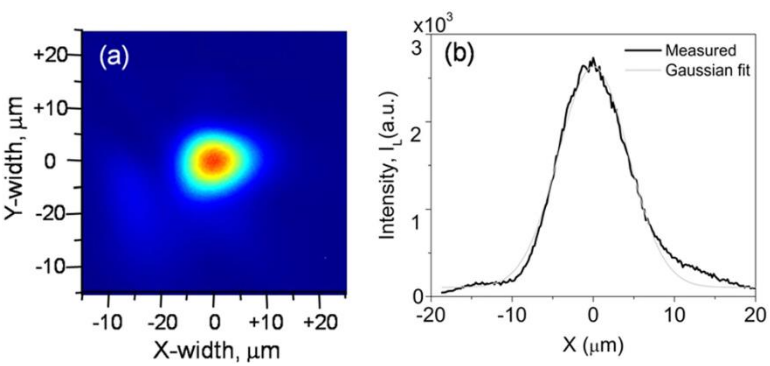
(With OAP:30cm, FWHM ~10 μm, I ~ 3×10^{18} W/cm^2)

Schematic of the experimental set-up

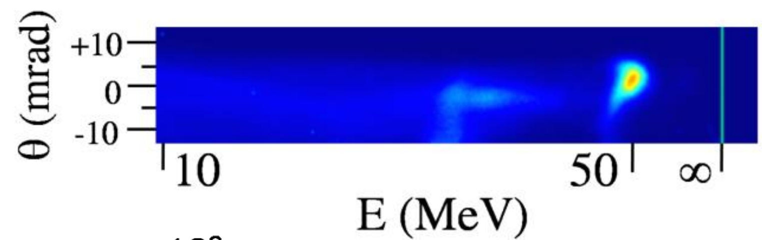


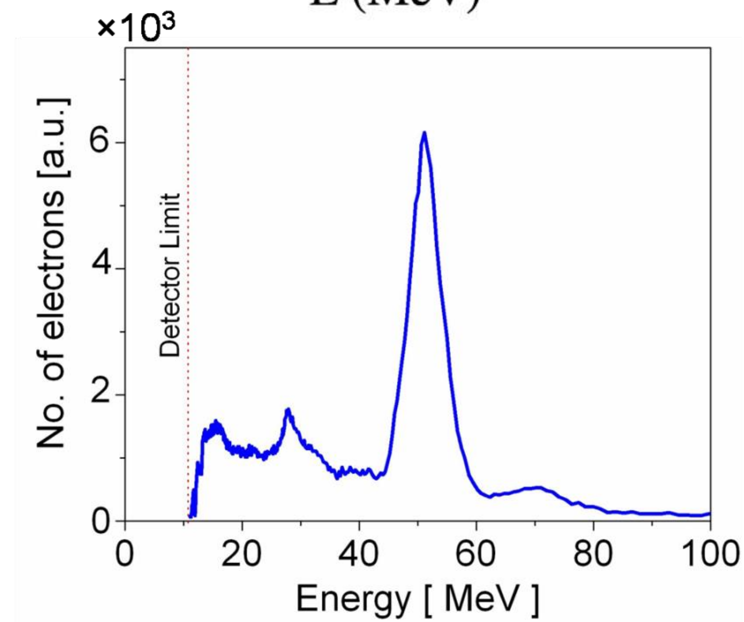
Laser focal spot

ω_0 = 9 µm, I = 3 x 10^{18} W/cm^2



Quasi mono-energetic electron beam



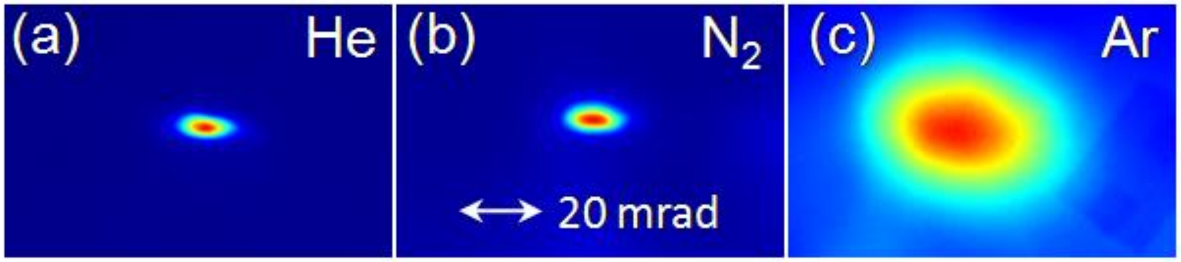


Phys. Plasmas 18, 093103 (2011)

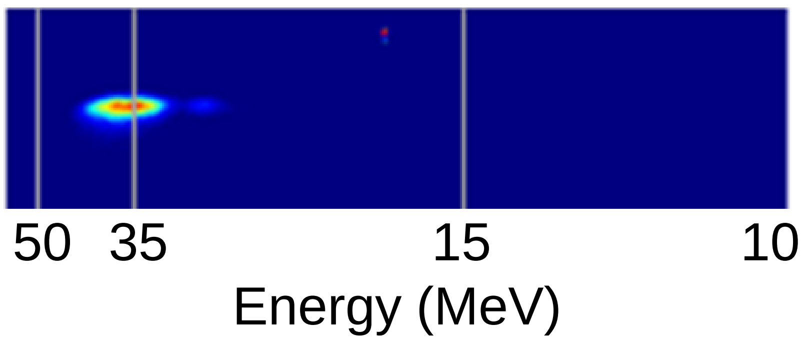
Experiments with Various Gases He, N_2 and Ar

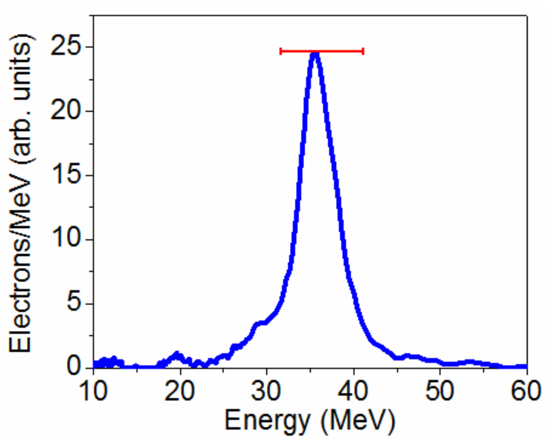
(OAP:27cm, FWHM ~7 μm, I ~ $5x10^{18}$ W/cm^2, No pre-plasma formation)

- High-quality, stable electron beam was produced from He and N_2 gas-jet targets. Electron acceleration in Argon gas jet was highly unstable.
- Electron beam profiles observed from different gases He, N_2 and Ar at electron density of 5.8×10^{19} cm^{-3}, 3.0×10^{19} cm^{-3}, and 3.0×10^{20} cm^{-3} respectively.



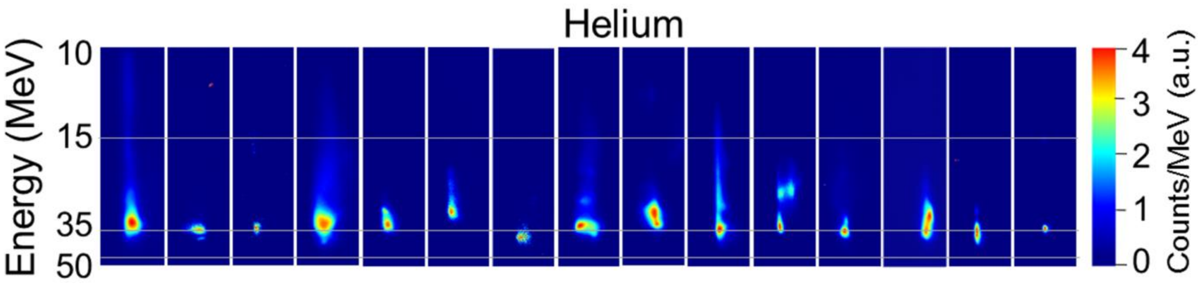
- A typical electron energy spectrum from He, at an electron density of ~5.8×10^{19} cm^{-3}.

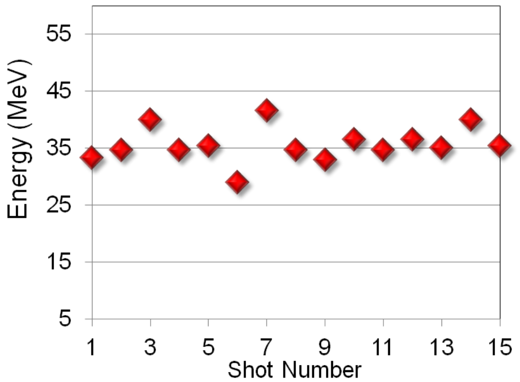




Recent Results with He, N_2 and Ar: contn…

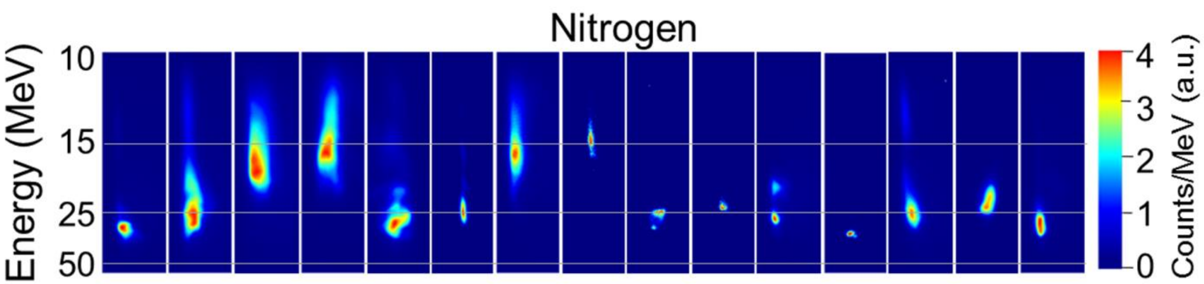
- Series of electron beam energy spectrum from He.





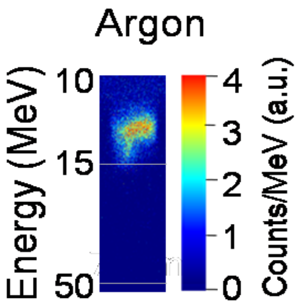
Phys. Rev. Spec. Topics 17, 011301 (2014)

- Series of electron beam energy spectrum from N_2.



Manuscript Under Review: PPCF

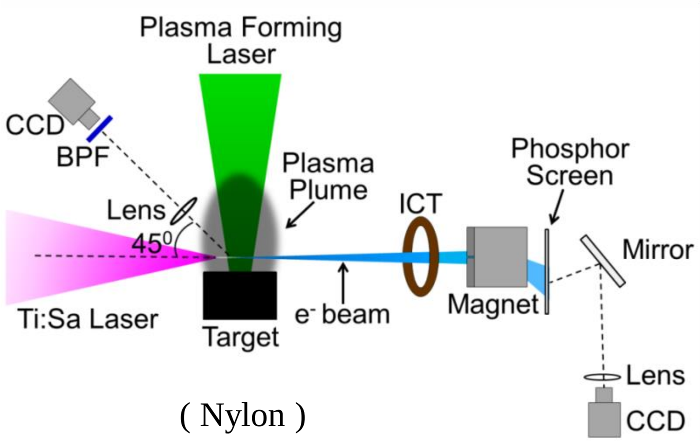
- Typical electron beam energy spectrum from Ar.



Quasi-mono-energetic electron beams with very low dark-current (background low energy electrons), divergence ~ 10 mrad, and peak energy of ~35 MeV and ~25-30 MeV, were produced from He and N_2 gas-jet targets, respectively. From Ar once in while a while large divergence beam with energy ~10 Mev was observed.

Laser wake-field acceleration in plasma plume

Experimental Set-up



(Nylon)

Laser guiding

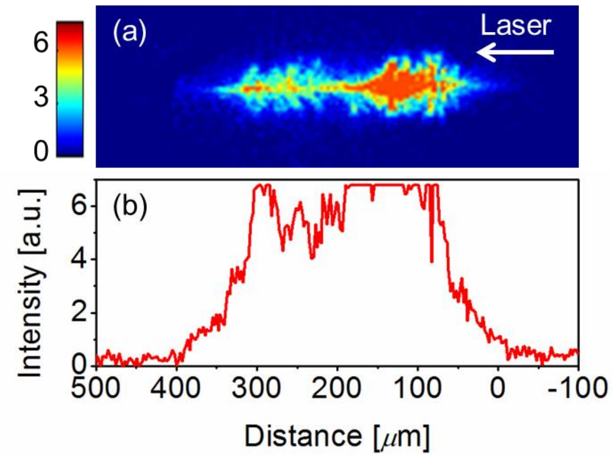
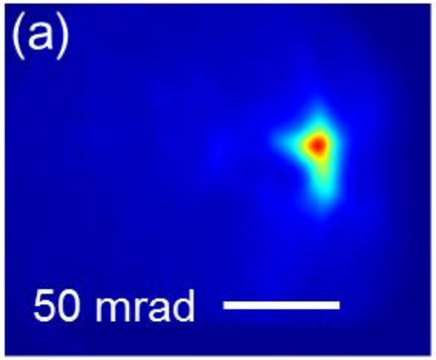
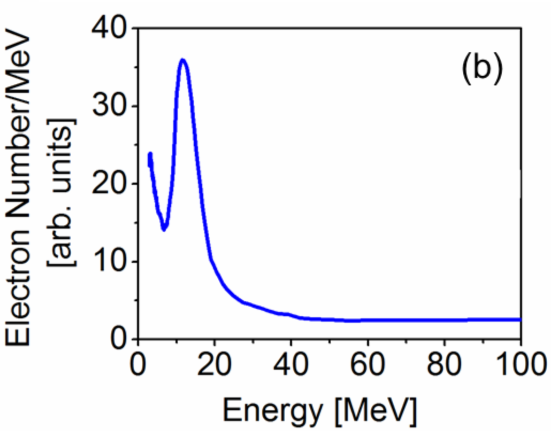


Image of Electron Beam



Energy spectrum



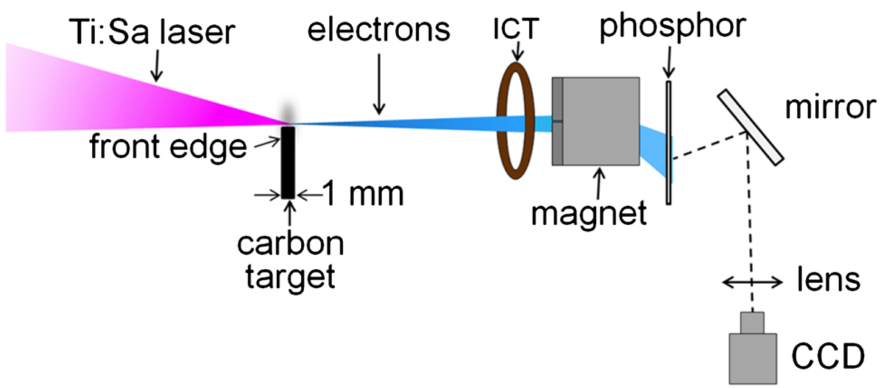
Plasma Forming Laser: part of 2ω (532nm) of Nd:YAG pump laser, 10 ns, 40mJ, focal spot ~200 μm, I ~ 10^{10}W/cm^2. Main Laser: 800nm, 45fs, 320mJ, focal spot ~8μm, I~5x10^{18} W/cm^2 . Delay between two laser pulses: 90 ns, Distance from target: 100-300μm.

- Ti:sapphire 45 fs laser pulse was guided over several Rayleigh lengths in the plasma plume as observed by the Thomson scattering side images of the interaction region.
- Quasi-monoenergetic electron beam with divergence~10 mrad, energy ~12 MeV, and charge ~100 pC, was observed at an optimum target distance of ~200 μm.

Appl. Phys. Lett. 102, 231108, 2013

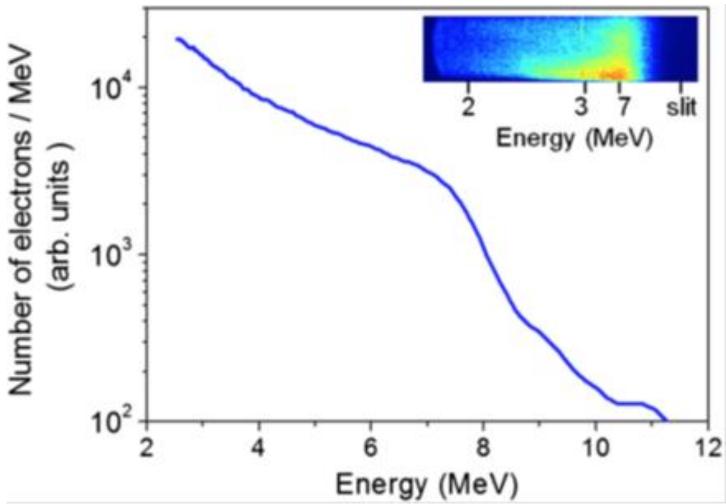
The scheme is simple and has the potential for high rep. rate operation.

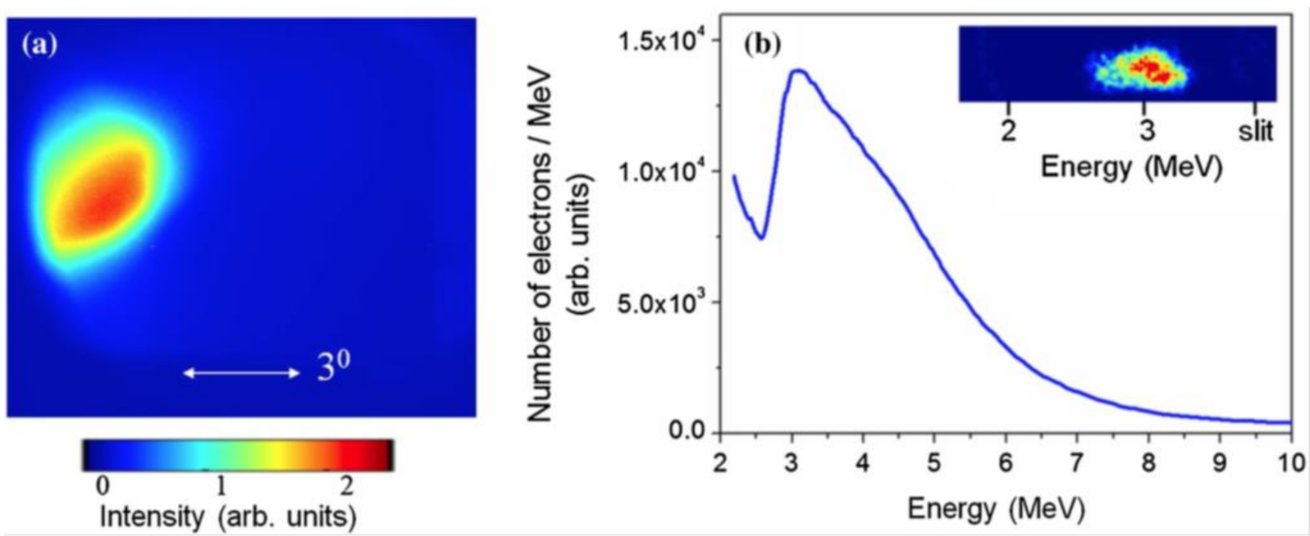
Electron Acceleration on Solid Surface at Grazing Incidence



We have studied the surface acceleration and generation of relativistic electron beam from the interaction of 45 fs laser pulses of intensity 5×10^{18} W cm^{-2} at grazing incidence on a carbon target. By controlling the laser pre-pulse, generation of collimated electron beam along the target surface direction with angular divergence ~3° and quasi-monoenergetic peak at ~3 MeV was observed. The high energy and quality of the electron beam are achieved by the choice of large angle of incidence (>80°) which facilitated efficient guiding and acceleration of electrons along the target surface. Such an electron beam with improved stability in future could be a potential candidate for many applications.

Electron Beam Spectra from Solid Surface Acceleration

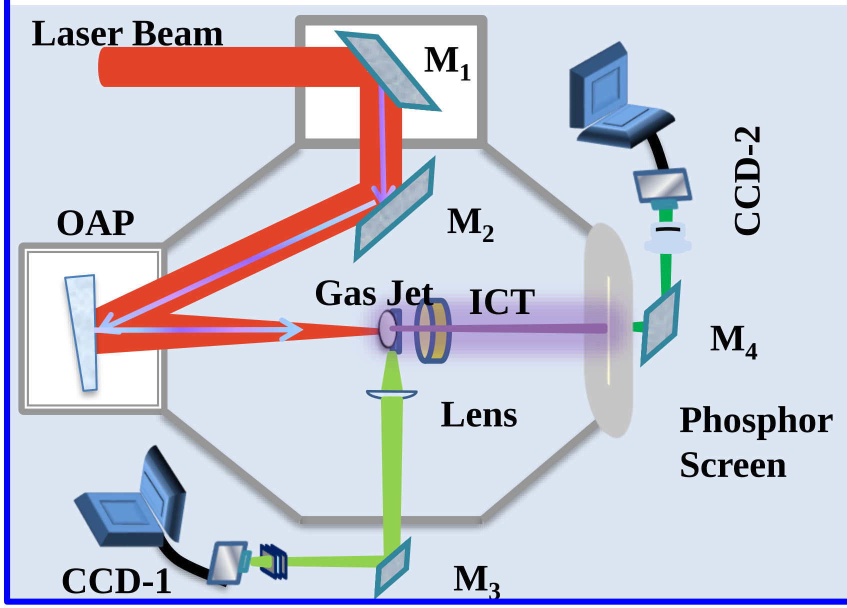




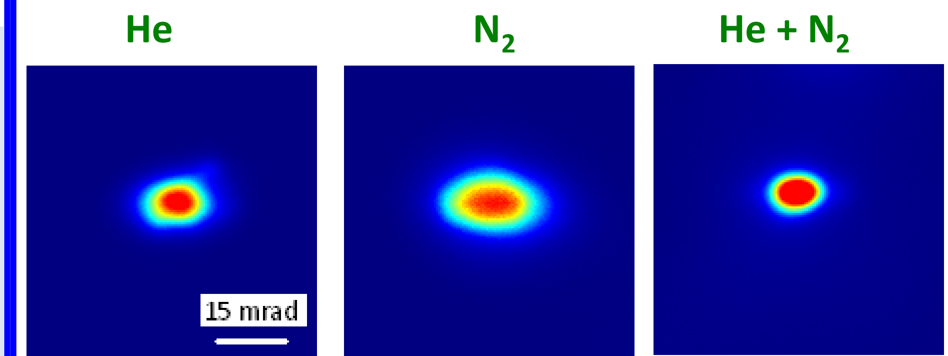
Appl. Phys. B 120, 149 (2015)

Laser Wakefield Electron Acceleration using 150 TW Laser

Experimental set-up

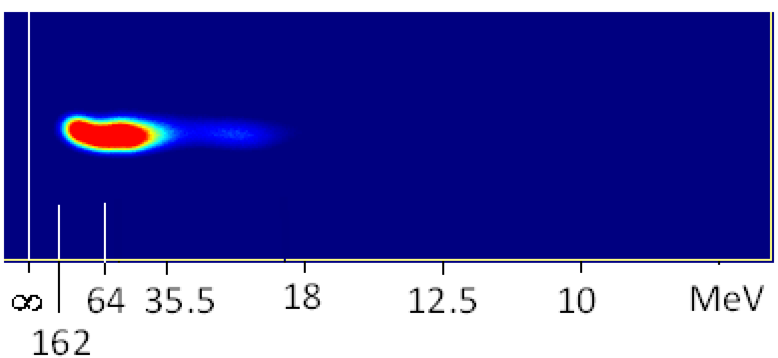


Electron Beam Profile

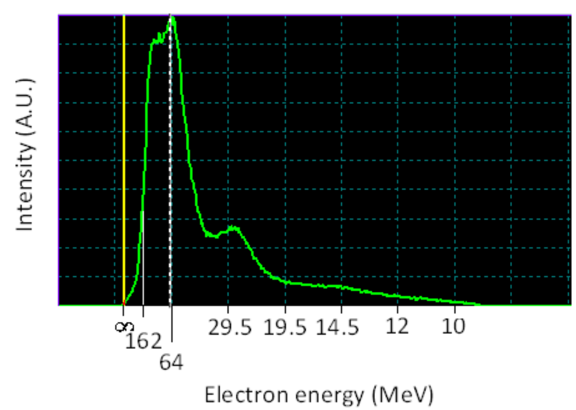


Electron beams of ~10 mrad divergence were observed.

Electron Beam Spectrum: He + N_2

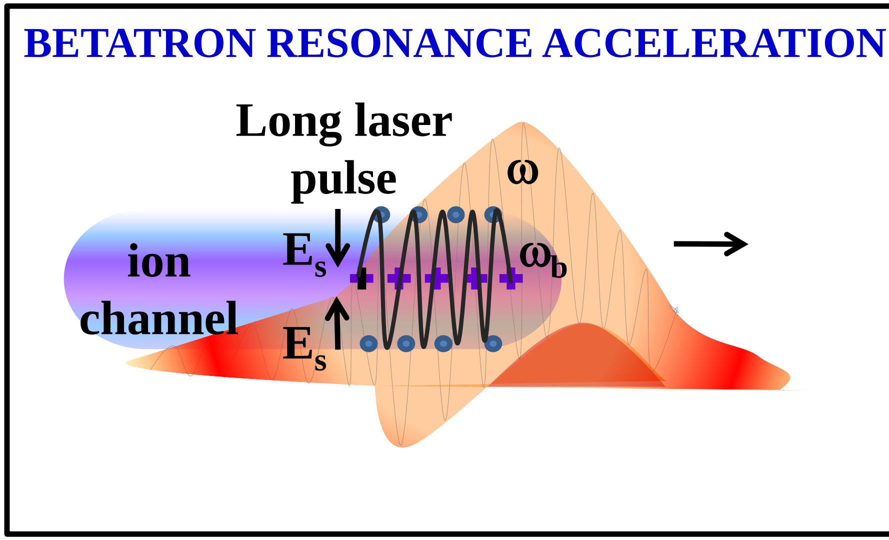


Electron Beam Spectrum Lineout



Betatron Resonance Acceleration using 150 TW Laser

- When high intense long laser pulses propagate through underdense plasma electrons are expelled from the laser propagation axis by the laser ponderomotive force, thus creating an ion channel.
- The electrons oscillate in the self generated static space charge field in the ion channel.



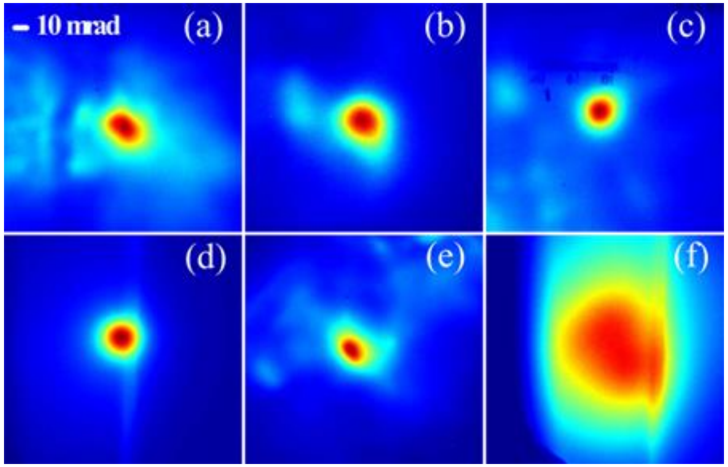
- The oscillation frequency is called betatron oscillation frequency ω_b

$$\omega_b = \frac{\omega_p}{\sqrt{2\gamma}}$$

where, ω_p is the plasma frequency
γ is the relativistic factor

- When this oscillation frequency equals laser frequency resonance occurs and laser energy is directly coupled to the electrons.
- The transverse energy gain is converted into the longitudinal component by the $(v \times B)$ force generated by the laser fields at this very high intensities.
- Higher the electron oscillation amplitude (x_T) and higher the phase velocity of the laser ($\eta=\sqrt{(1-\omega_p^2/\omega^2)}$) higher is the energy gain.

Electron Beam Spatial Profiles



(a) $n_e = 3.6 \times 10^{19} cm^{-3}$
(b) $n_e = 4 \times 10^{19} cm^{-3}$
(c) $n_e = 5 \times 10^{19} cm^{-3}$
(d) $n_e = 6 \times 10^{19} cm^{-3}$
(e) $n_e = 8 \times 10^{19} cm^{-3}$
(f) $n_e = 9 \times 10^{19} cm^{-3}$

P=7.5 TW in laser focus
$I=2.12\times10^{18}$ W/cm^2
$a_0=1$
$n_e=3.6\text{-}11\times10^{19}$ cm^{-3}
$P/P_c= 9\text{-}28$

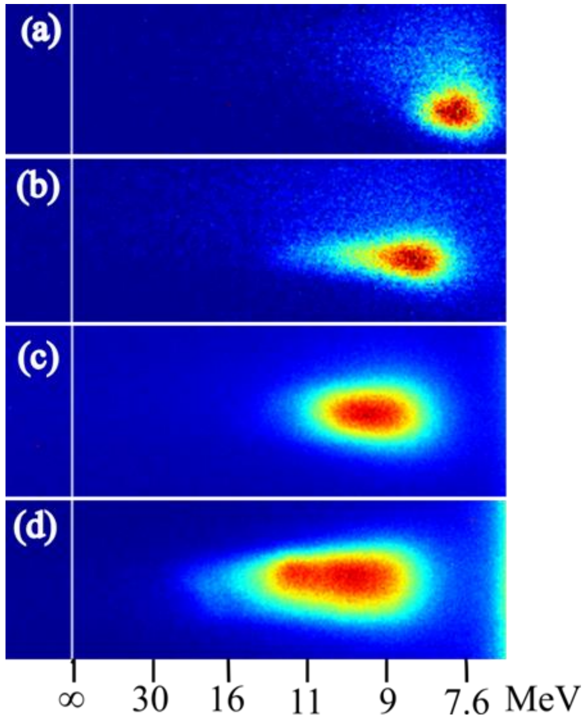
P_c is the critical power for self focusing and guiding and is given by

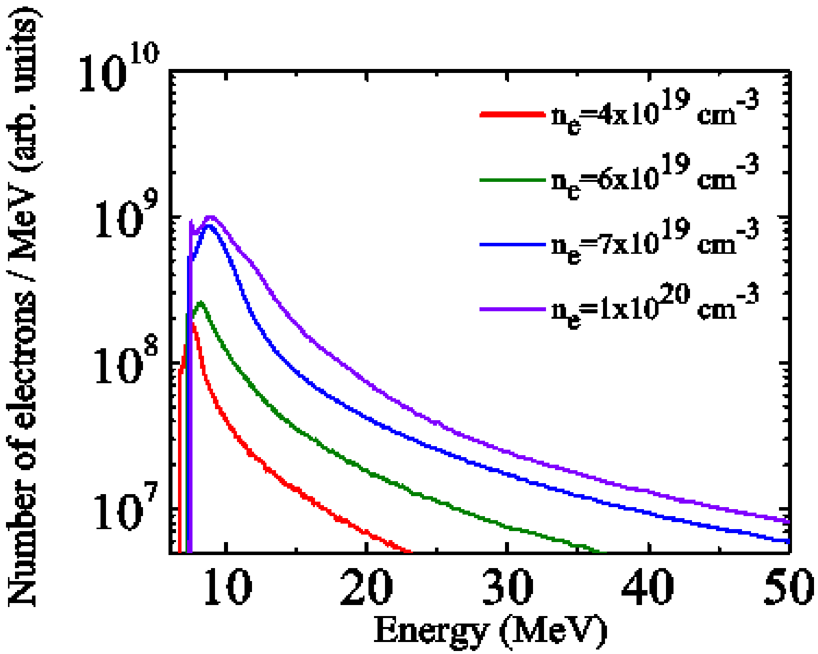
$$P_c=17.4\times(\omega/\omega_p)^2 \text{ (GW)} =17.4\times n_c/n_e \text{ (GW)}$$

Where,
ω is the laser frequency
ω_p is the plasma frequency
n_c (cm^{-3})$=1.1\times10^{21}/\lambda^2(\mu m)$ is the critical density

Collimated electron beams in laser propagation direction for plasma density in the range of ~3.6-8 × 10^{19} cm^{-3}
Divergence ~40 mrad
At higher density divergence increased to ~120 mrad

Single Electron Beam Spectra





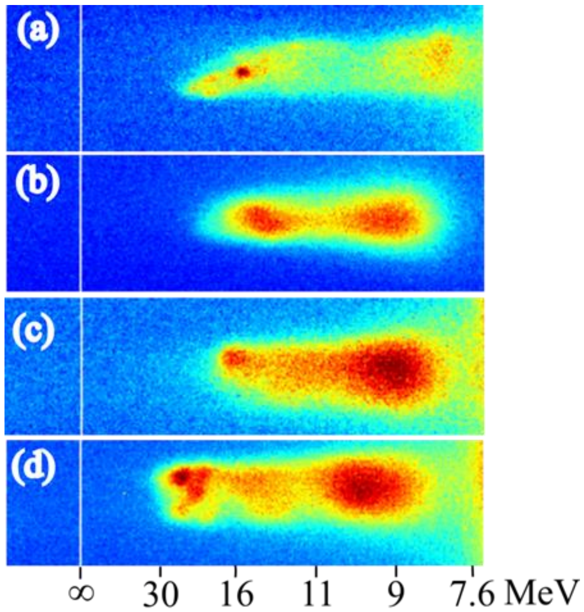
Quasi-monoenergetic electron beams with average peak energy ~8-11 MeV

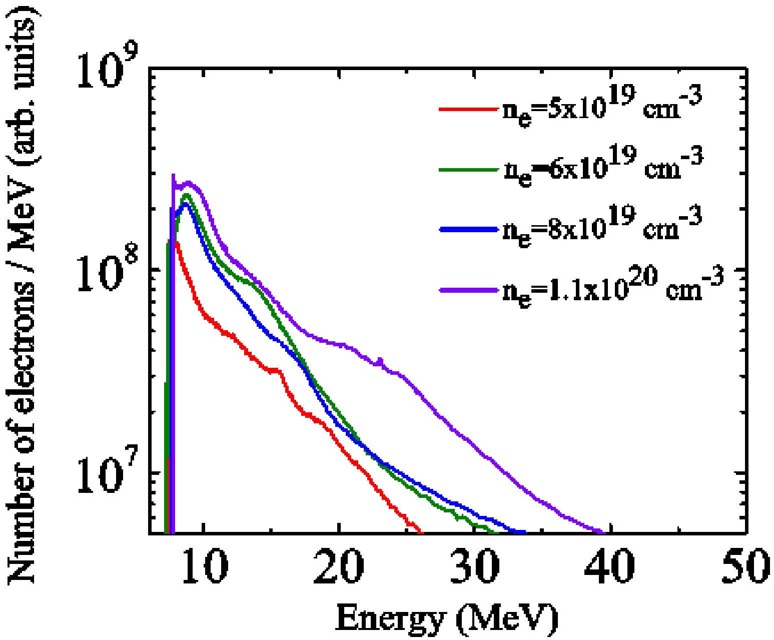
Divergence ~20mrad, $\Delta E/E$=15%

Increase in electron energy with density.

Dual Electron Beams Spectra

Dual or multiple beam formation with quasi-monoenergetic features.





First beam peak energy: 8-10 MeV,

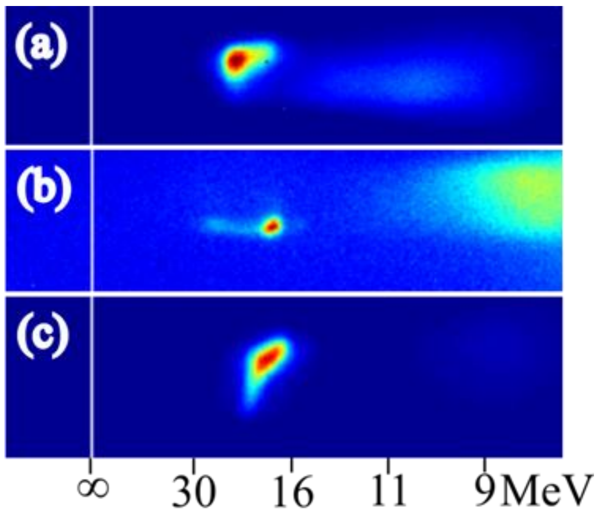
Second beam peak energy: 12-25 MeV

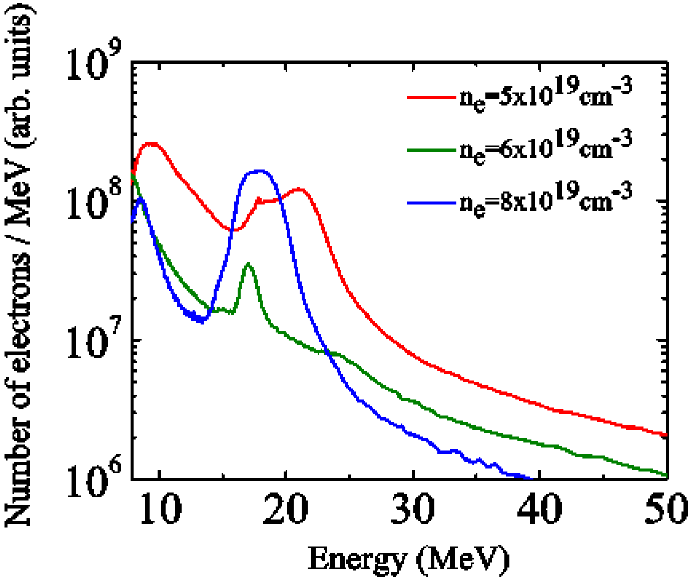
Maximum energy of electrons ~30 MeV

Increase in electron energy with density.

Single Quasi-monoenergetic Electron Beams

In several shots highly collimated quasi-monoenergetic electron beams were observed

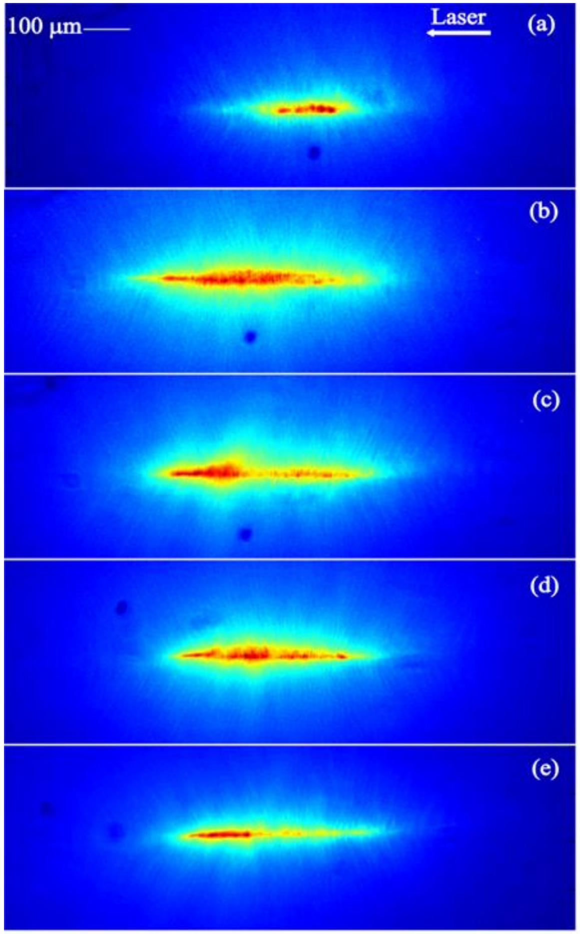


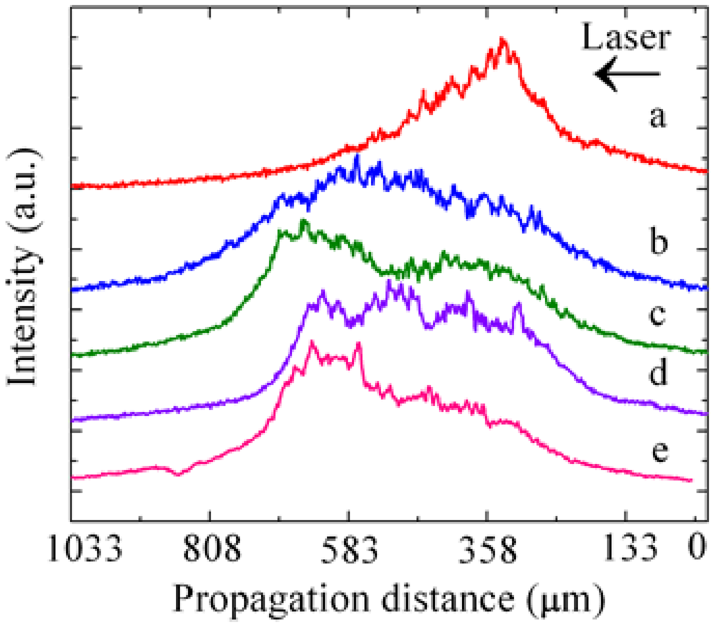


Peak energy ~ 17-22 MeV, Divergence <10 mrad, , ΔE/E ~27%

Generation of such quasi-monoenergetic electron beams accelerated through betatron resonance acceleration mechanism has not been reported till date.

Laser Channels Inside Plasma





Relativistic self-focusing and channelling of the laser pulse was observed.

For plasma density of 3.6-4x10^{19} cm^{-3} channel length was ~255μm (~1.4 Z_R) (Fig. a).

With increase in the plasma density channel lengths increased to ~500-550 μm (~2.8-3 Z_R) (Fig. b &c).

With further increase in the plasma density decreased to ~450 μm (~2.5 Z_R) (Fig.d and e).

In the later part of the propagation magnetic constriction of channel was observed.

Laser Driven Electron Acceleration

Summary and Future Plan

10TW, 45 fs Ti:Sapphire Laser System

Operational Since May 2006.

Extensively used for Laser Wakefield Electron Acceleration.

Generated ~50 MeV electron beams in 0.5mm plasma length.

150TW, 25fs Ti:Sapphire Laser System

Recently Installed.

Generated >100 MeV electron beams in 0.5mm plasma length.

Attempts towards generating 0.5 -1 GeV electron beams using longer plasma length in progress.

Quasi-monoenergetic electron beams by Betatron Resonance Acceleration

1 PW, <25fs Ti:sapphire Laser System

Purchase Order Released

Installation due in the beginning of next year (2018)

Acknowledgements

Experimental Group

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