USj-WS on HIF & HEDP
at Utsunomiya
29 Sep,. 2005

Monoenergetic Acceleration of Electrons by Laser-Driven Plasma Wave

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Outline

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- **Monoenergetic electron acceleration with a laser power of 2-TW.**

  Moderately high density plasmas (≈10^{20}cm^{-3}) were used for electron acceleration.

  ***E*≈7-15MeV**

- **Monoenergetic electron acceleration with a laser power of 3-4TW.**

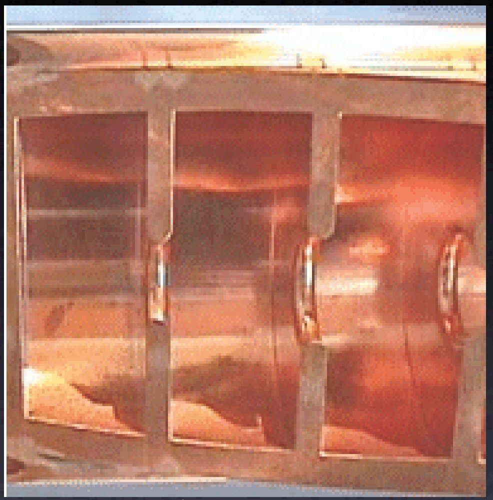
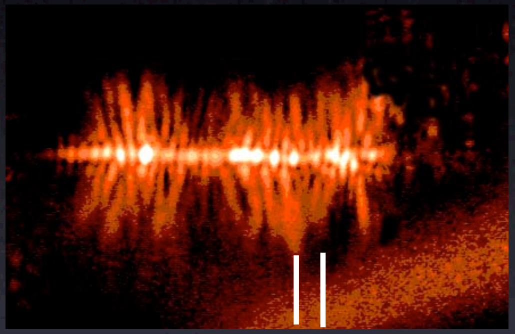
  Monoenergetic beams were produced at the density of approximately (4-5)x10^{19}cm^{-3}.

  The focal length ≈ 300mm (160mm at the previous experiment)

  ***E*≈18-25MeV**

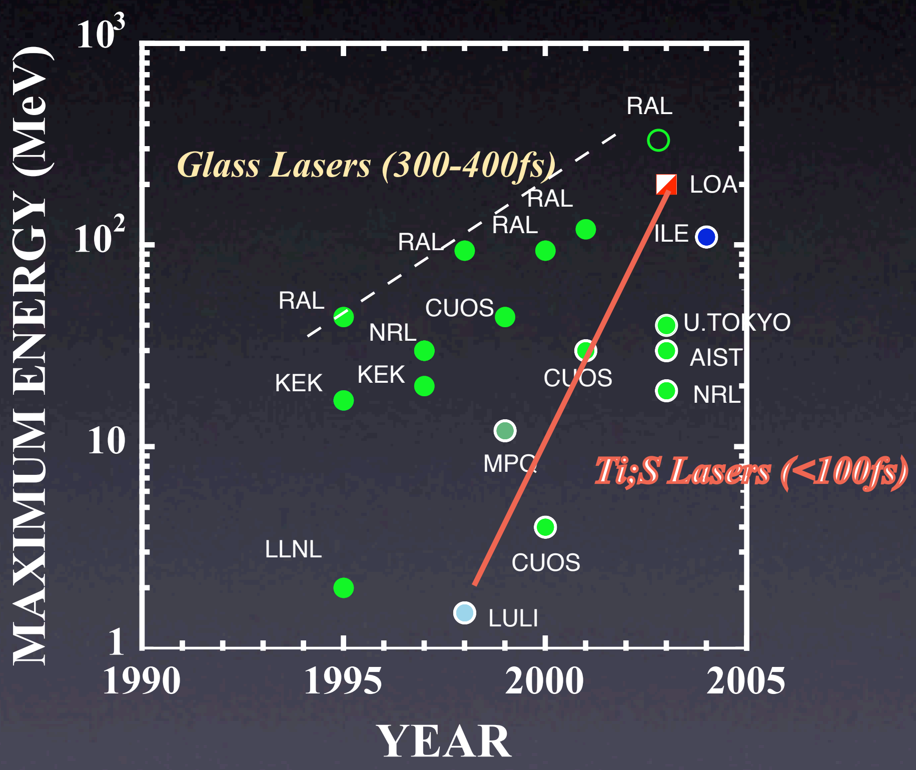
- **Empirical scaling law of monoenergetic acceleration of electron.**

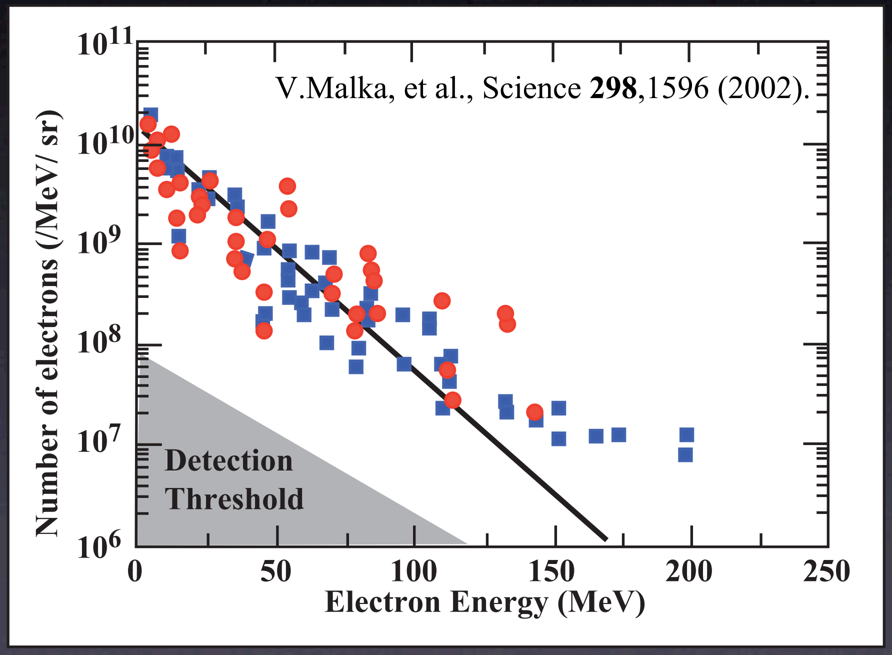
Rf-linac and Laser-accelerator

	Rf-linac	Laser-plasma Accelerator
Characteristic Scale Length	 Several-cm〜10-cm	 Several- μm〜100-μm
Structure	Metal electrodes	Plasma (pulse)
Field Gradient	10-100 MeV/m	10-100 GeV/m
Length to get 1GeV	10-100 m	1-10 cm
Bunch length	pico-second	femto-second
Present Status	mature technology	a lot of problems

Laser-plasma Particle Accelerator

Growth and Problem





Maximum Acceleration Energy grows >100 times and reaches >200MeV in this decade.

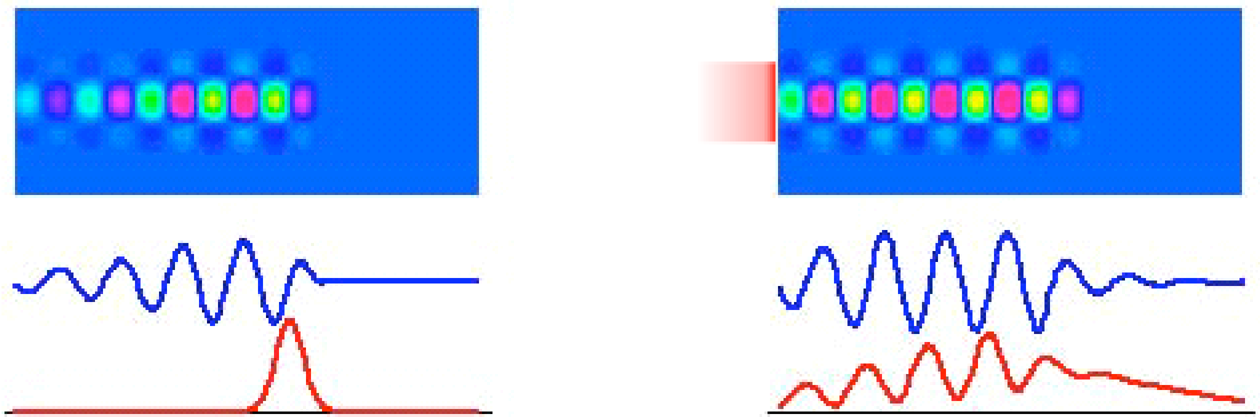
However, the energy spectrum of electron bunch was very wide (Boltzman-like distribution).

Principle of Laser-plasma Particle Accelerator

$\omega_p \tau_L \approx \pi$ $\omega_p \tau_L > \pi$

ELECTRON DENSITY

LASER PULSE



Electrons are expelled by the ponderomotive force of the laser pulse.

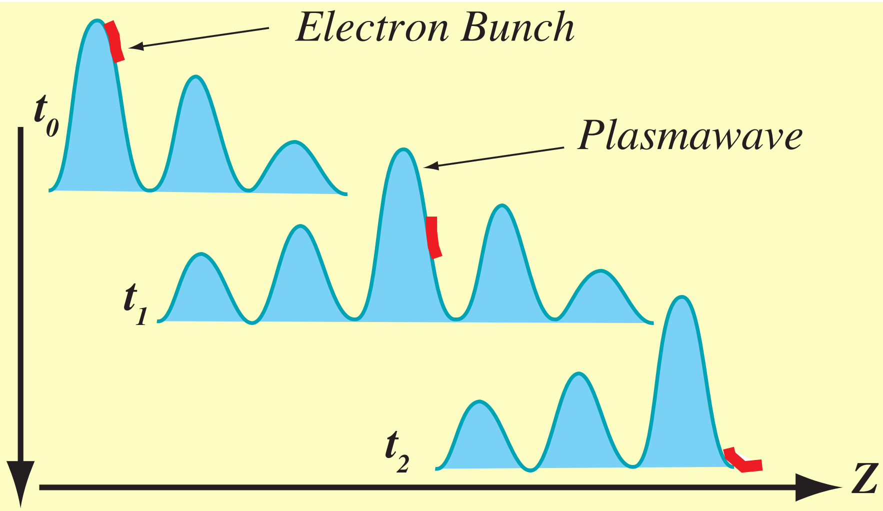
Electrons plasma wave is excited after the pulse.

Laser Wakefield Accelerator — Self-modulated Laser Wakefield Accelerator

T. Tajima and J. M. Dawson, "Laser Electron Accelerator", Phys. Rev. Lett. 43, (1979),267-270

For mono-energetic acceleration

- ❖ A small number of (≈single) potential well
  - $\omega_p \tau_L \approx \pi$ ➟ rapid decay
  - $\omega_p \tau_L > \pi$ ➟ slow growth & rapid decay
- ❖ Localized trapping of electrons (local breaking)
- ❖ No wavebreaking during the acceleration



Another Acceleration Scheme of mono-energetic acceleration (Bubble acceleration / Bullet regime)

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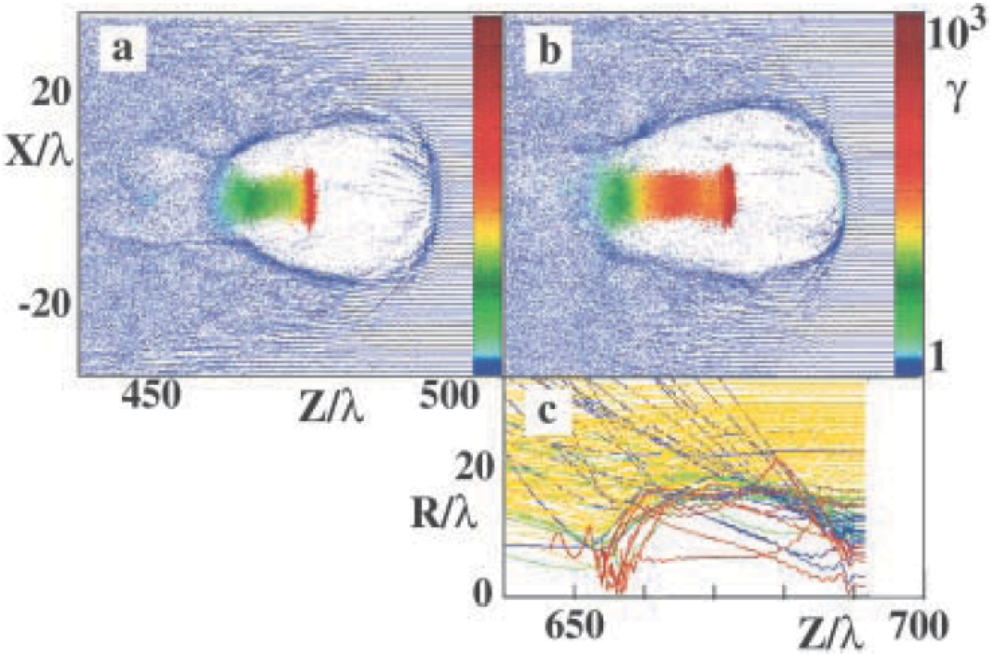
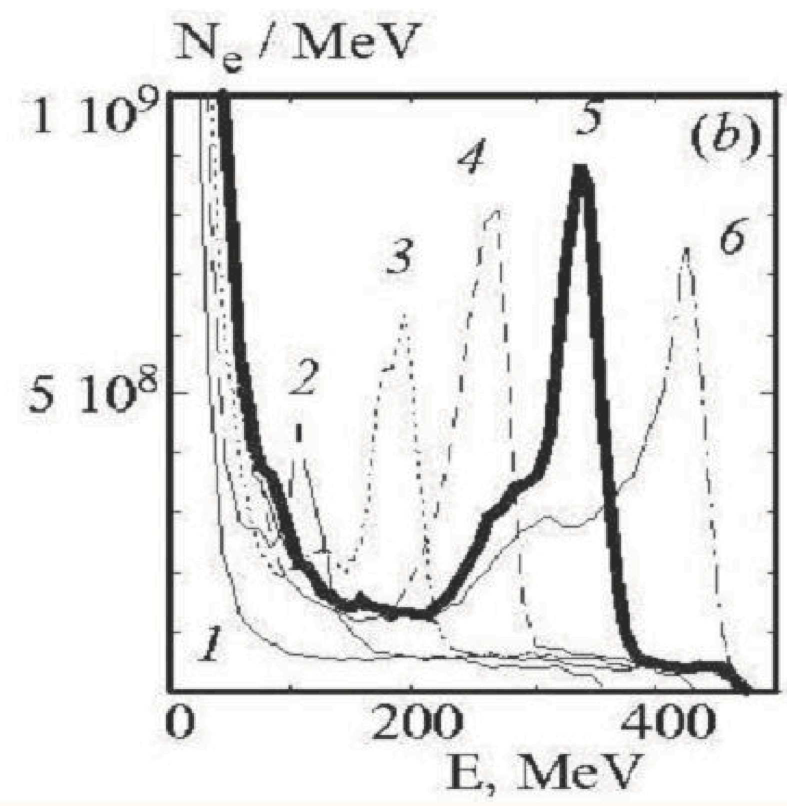


FIGURE 4 Solitary laser-plasma cavity produced by 12-J, 33-fs laser pulse. **a** $ct/\lambda = 500$, **b** $ct/\lambda = 700$, **c** electron trajectories in the frame moving together with the laser pulse; *color* distinguishes electron groups with different distances from the axis initially

$$\omega_p \tau_L \leq \pi$$

laser	cycles
1	350
2	450
3	550
4	650
5	**750**
6	850



A. Pukhov, J. Meyer-ter-vehn,

Appl. Phys. B 74, 355–361 (2002)

Schematic Drawing of Experimental Setup

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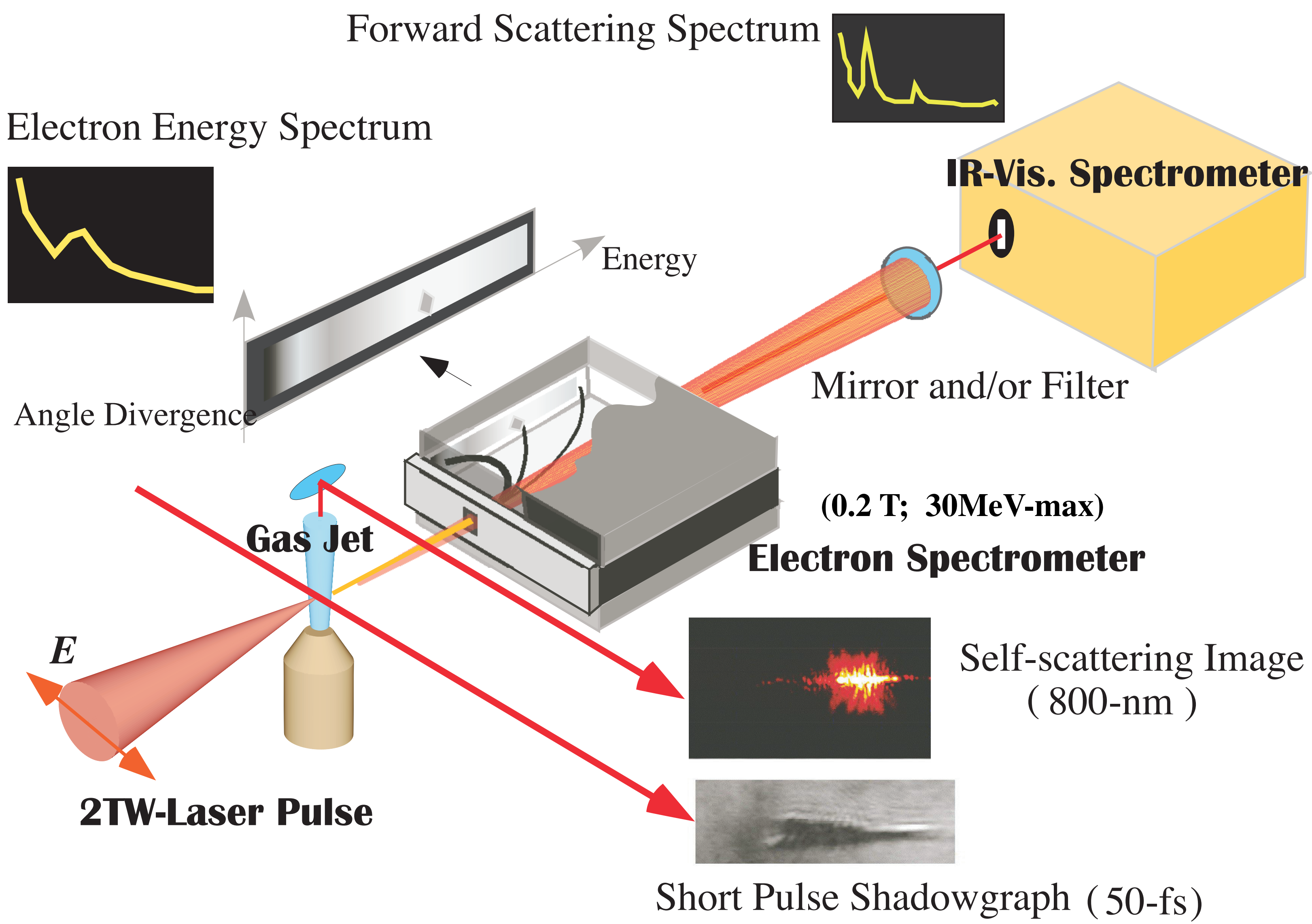

Layout in the Target Chamber

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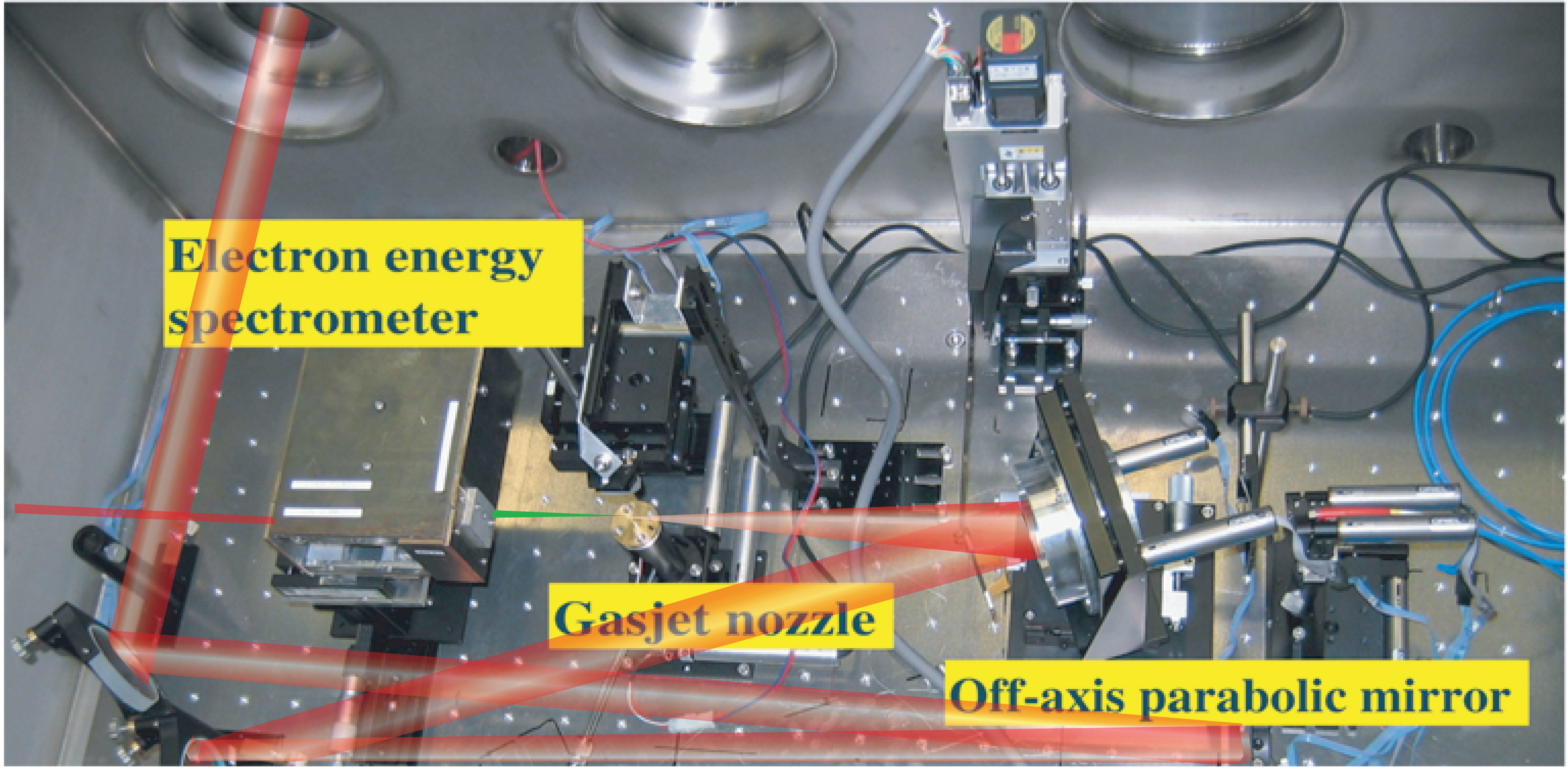

Experimental Condition

LASER

Ti:sapphire laser
- Wavelength ; 800 nm
- Power ; 2 TW
- Pulse width ; 50 fs
- Focus diameter ; 5µm (w_0=4.3µm)
- F & (focal length) ; 3.5 (165 mm)

Focus Intensity ; 5x10^{18} W/cm^2 (a_0=1.5)

TARGET

Supersonic gas jet
- Gas ; N_2, He
- Reservoir pressure ; 2 -8 MPa (20-80 bar)
- Mach number ; ≈ 3 - 4 (for N_2)

PLASMA DENSITY (≈Neutral density & BSI-model)

(0.4-4.4)x10^{20} cm^{-3} ; N_2 (5+ at I_L >10^{18} W/cm^2)

(0.4-1.3)x10^{20} cm^{-3} ; He

Spectrum of Monoenergetic Electron beam

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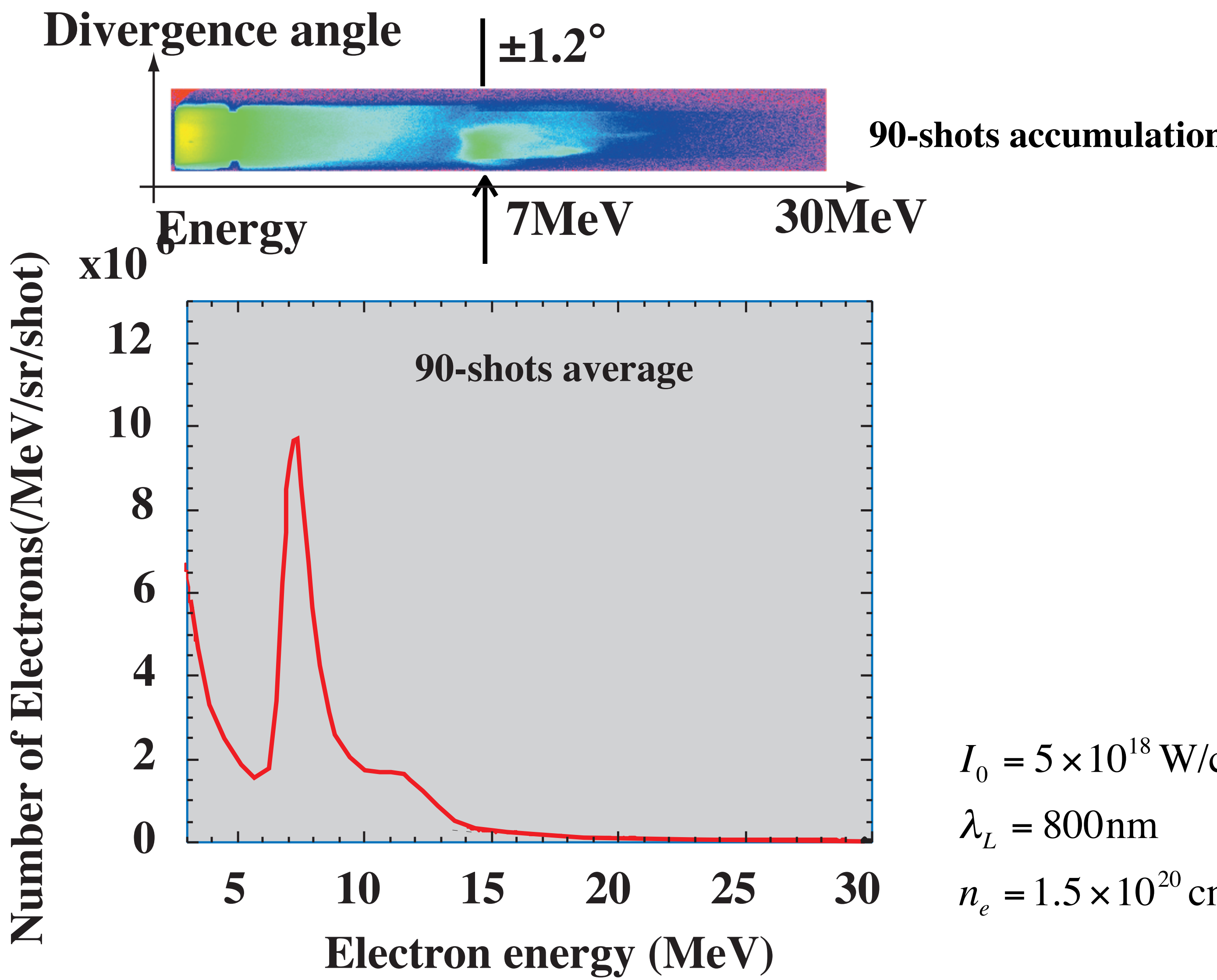

$I_0 = 5 \times 10^{18}\,\mathrm{W/cm^2}\ (a_0 \approx 1.5)$

$\lambda_L = 800\mathrm{nm}$

$n_e = 1.5 \times 10^{20}\,\mathrm{cm^{-3}}$

Normalized emittance $\varepsilon_n = \gamma\sigma\delta\theta \approx 0.7\pi$ mm mrad

E.Miura, K.Koyama, S.Kato, N.Saito, M.Adachi, Y.Kawada, T.Nakamura, and M.Tanimoto; Appl. Phys. Lett., Vol.86, 251501,

Spectra of Electron Energy and Forward Scattering

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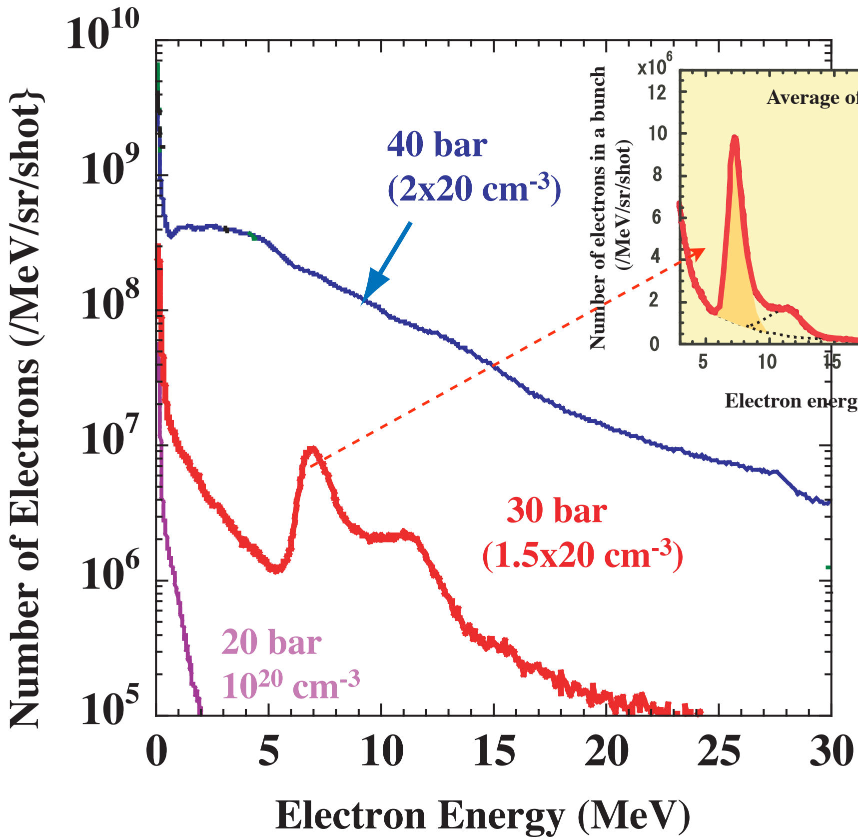

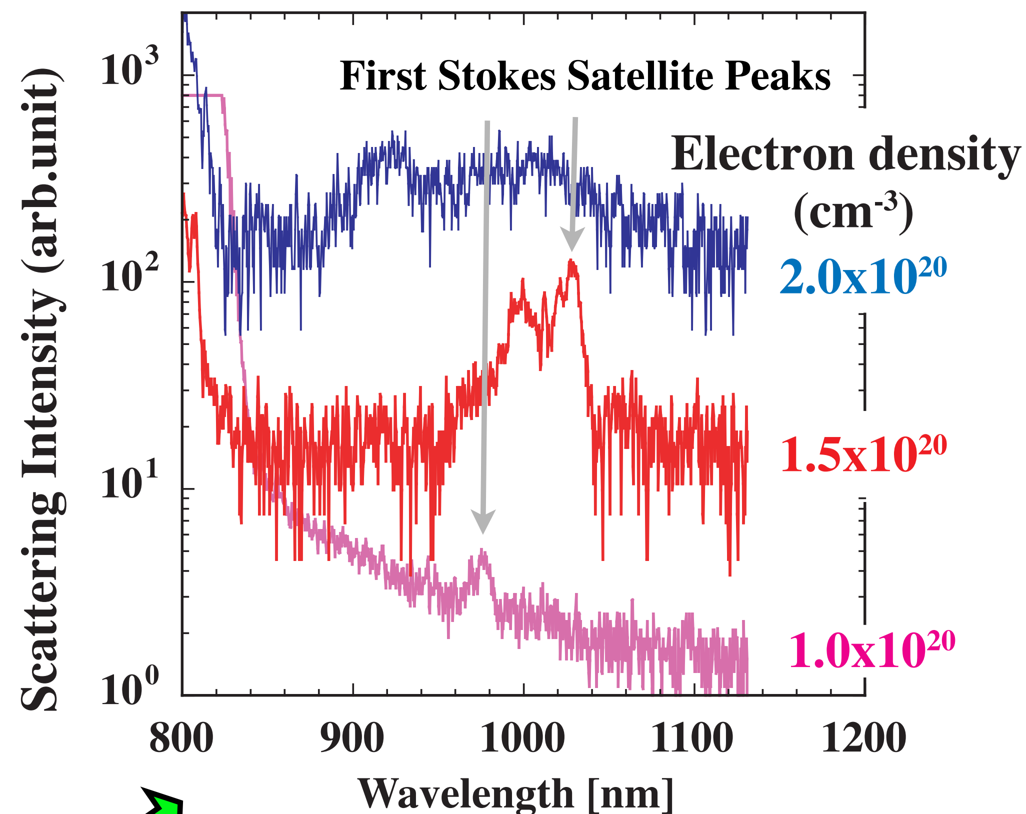

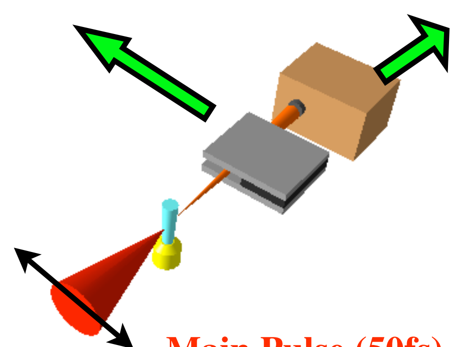

Stokes satellite peaks grow large while the n_e is increasing from 10^{20} to $1.5\mathrm{x}10^{20}$ cm^{-3}.
Stokes satellite become intense and broad at $n_e > 2\mathrm{x}10^{20}$ cm^{-3}.

Side Scattering Image and Side-view of Shadowgraph

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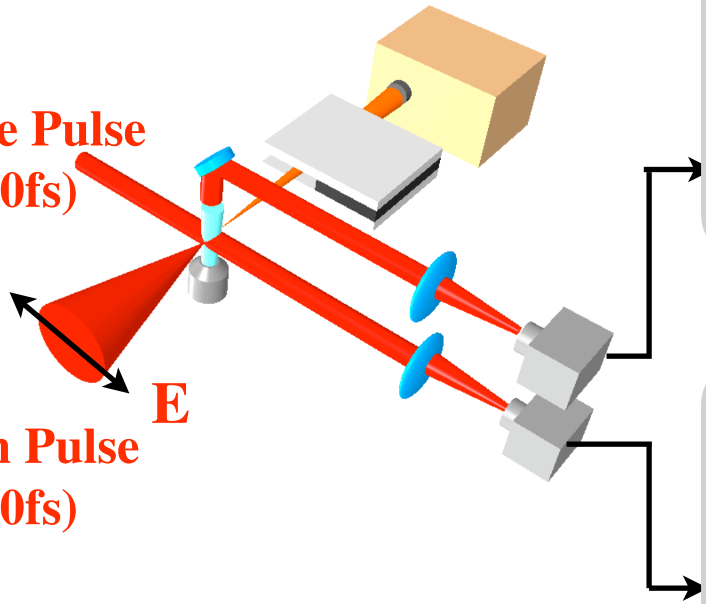
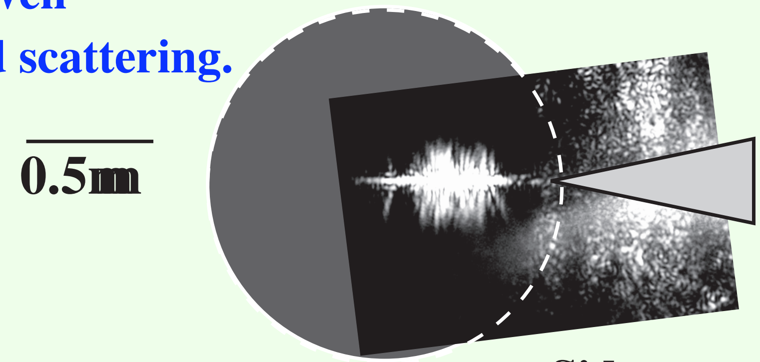
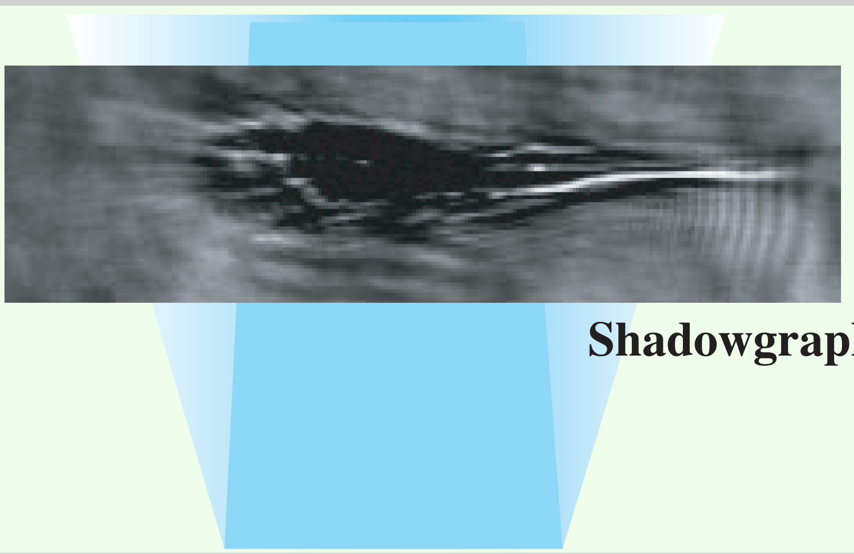
- A fishbone structure of the side scattering well correlated with Stokes satellites of forward scattering.
- Side scattering is quite intense.





Scattering of Main pulse



- Coherent scattering by the plasma wave.
- Terminated by breakup of the laser beam.

Plasma wave propagated ≈500μm (>> the dephasing length).

Electron Energy Spectra for Different Electron Densities

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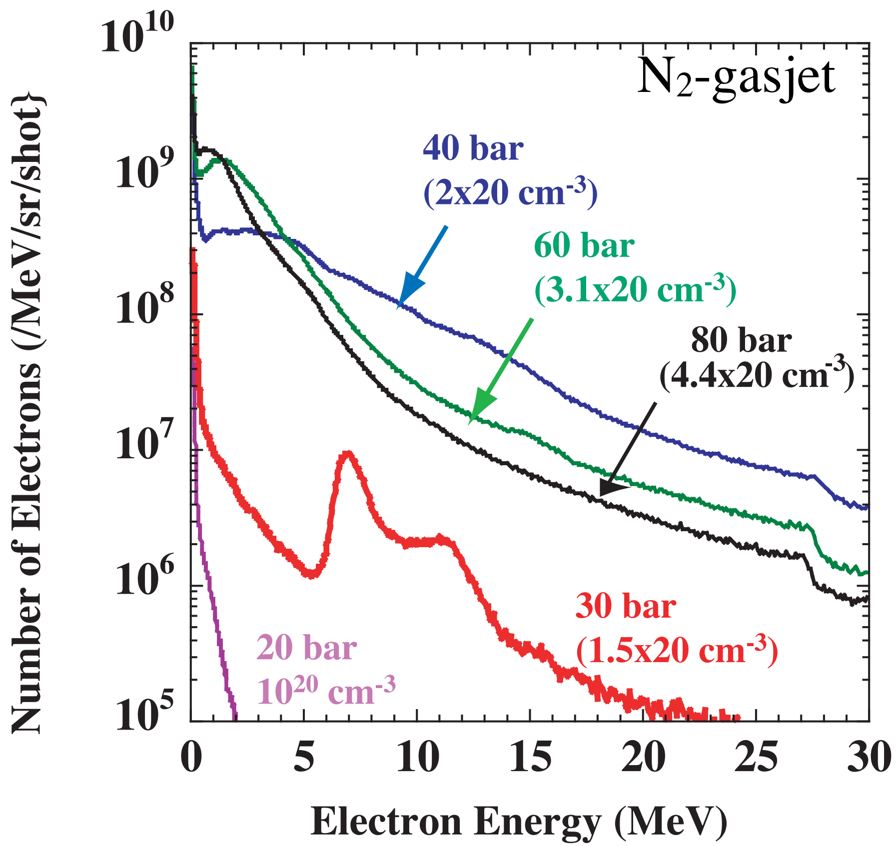
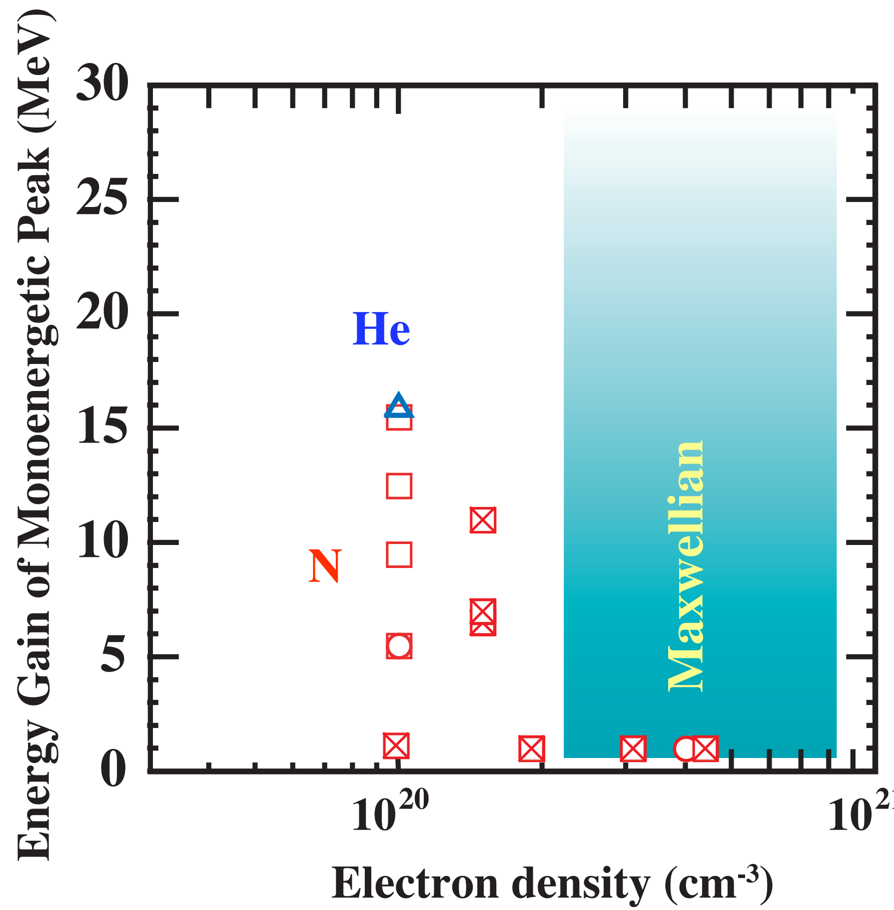
$$I_L = 1.5 \times 10^{18}\ \mathrm{W/cm^2}$$





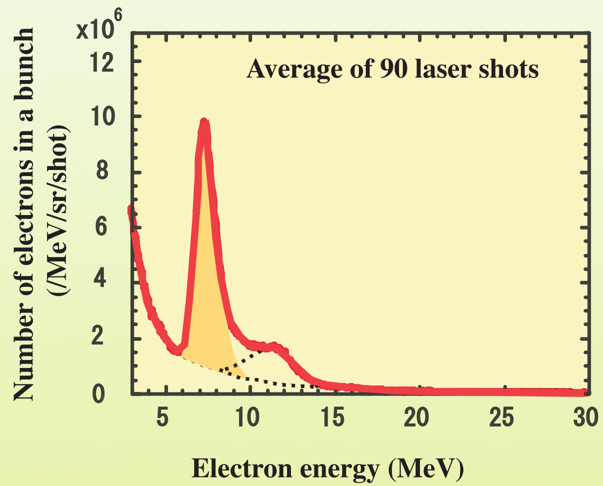
High Density ; huge number of electrons
Maxwellian Distribution

Low Density ; no high-energy electron

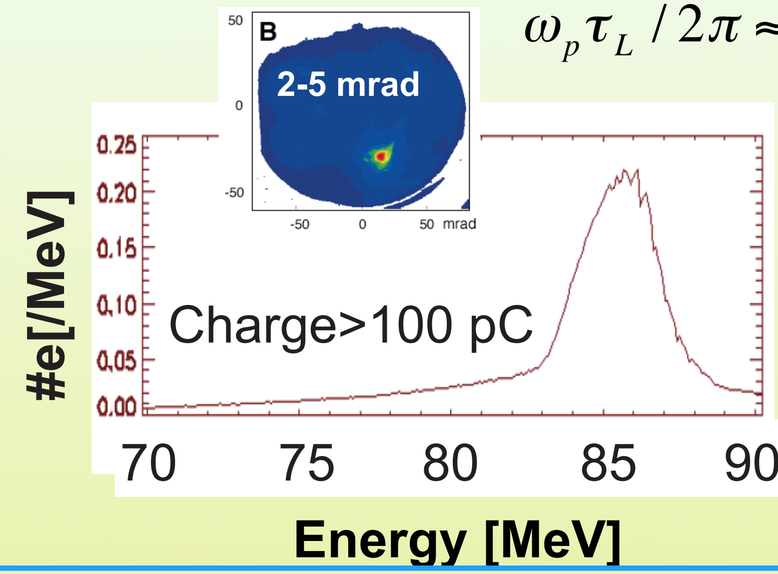
Monoenergetic electron beam is accelerated in the narrow region of the density.

Mono-energetic spectra at various electron densities

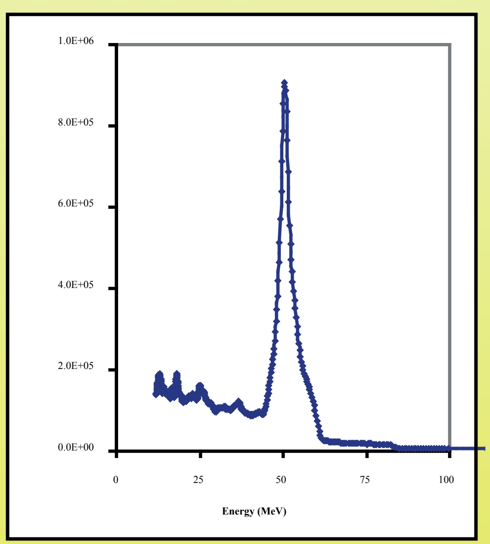
AIST **2TW-50fs** $\omega_p \tau_L / 2\pi \approx 5.5$



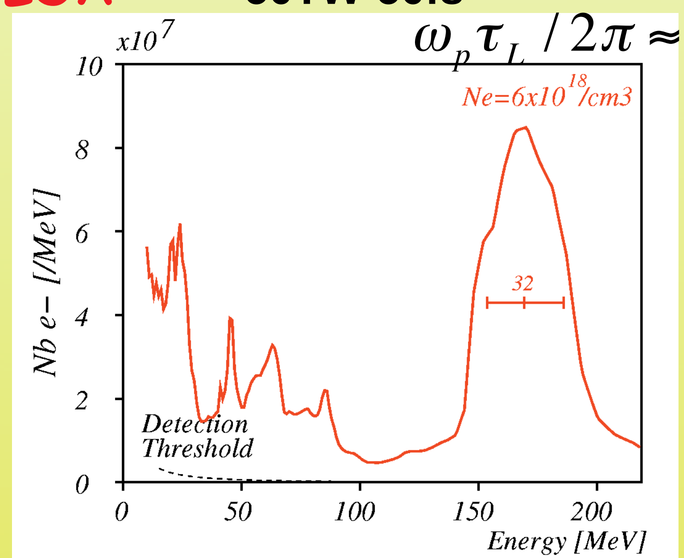
LBNL **8TW-55fs Guided** $\omega_p \tau_L / 2\pi \approx 2.2$



RAL **16TW-40fs** $\omega_p \tau_L / 2\pi \approx 1.6$



LOA **30TW-30fs** $\omega_p \tau_L / 2\pi \approx 0.66$



Empirical Scaling-law of Laser-Plasma Accelerator

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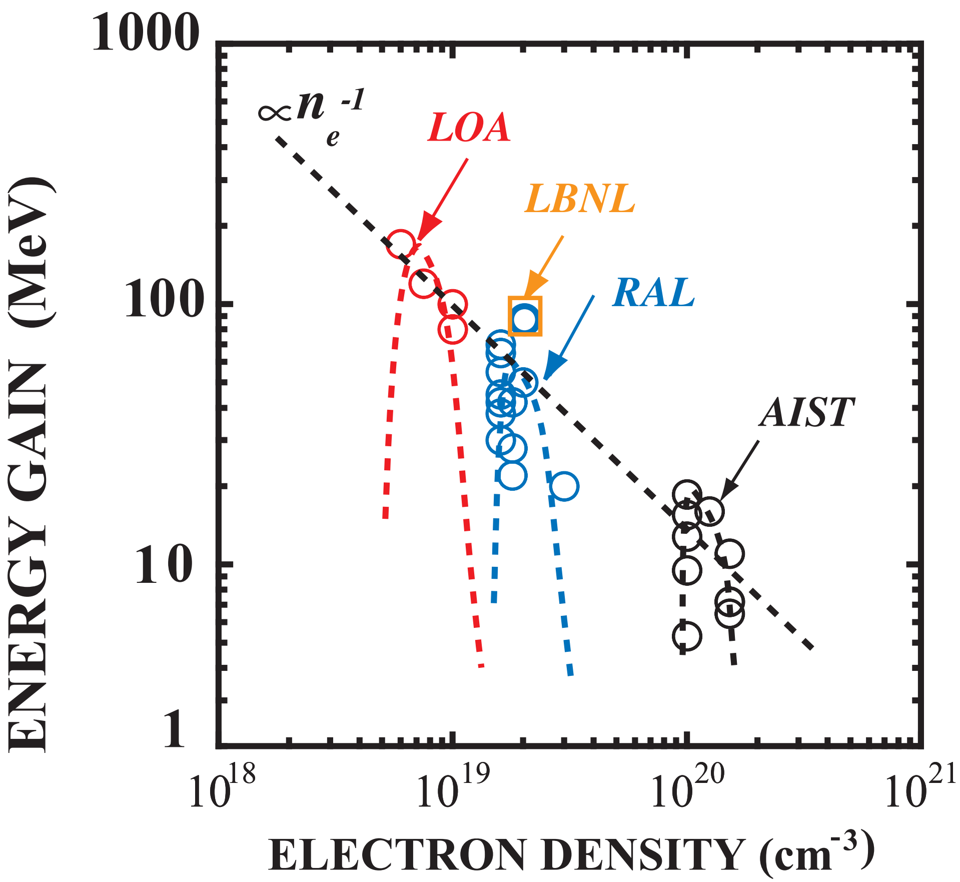
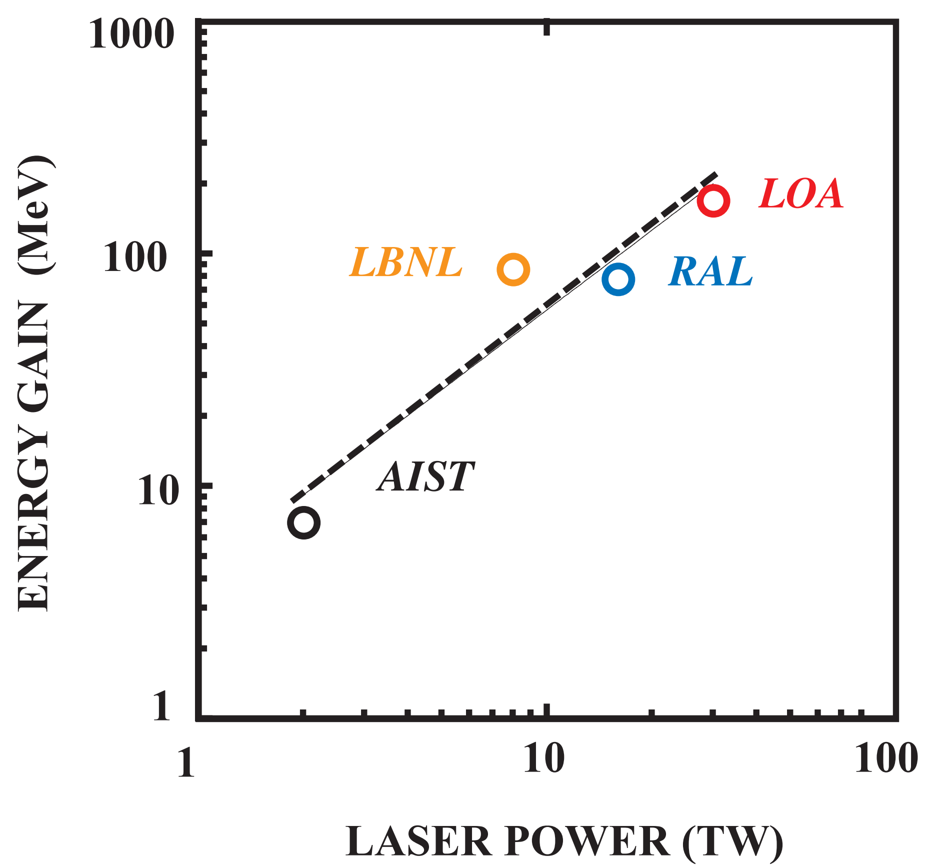
LOA ; 30TW, 30fs, $1.5 \times 10^{18} W/cm^2$
RAL ; 16TW, 40fs, $1.5 \times 10^{18} W/cm^2$
LBNL; 8TW, 50fs, $1.0 \times 10^{19} W/cm^2$ Guided
AIST ; 2TW, 50fs, $1.5 \times 10^{18} W/cm^2$





For increasing energy gain and number of electrons

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Energy gain

Lower electron density (long dephsing length)

Number of electrons

Large beam diameter
long plasma wavelength
Large density modulation

Solution is

Large focal spot and Large laser power

Long focus

Experiments with a long focus

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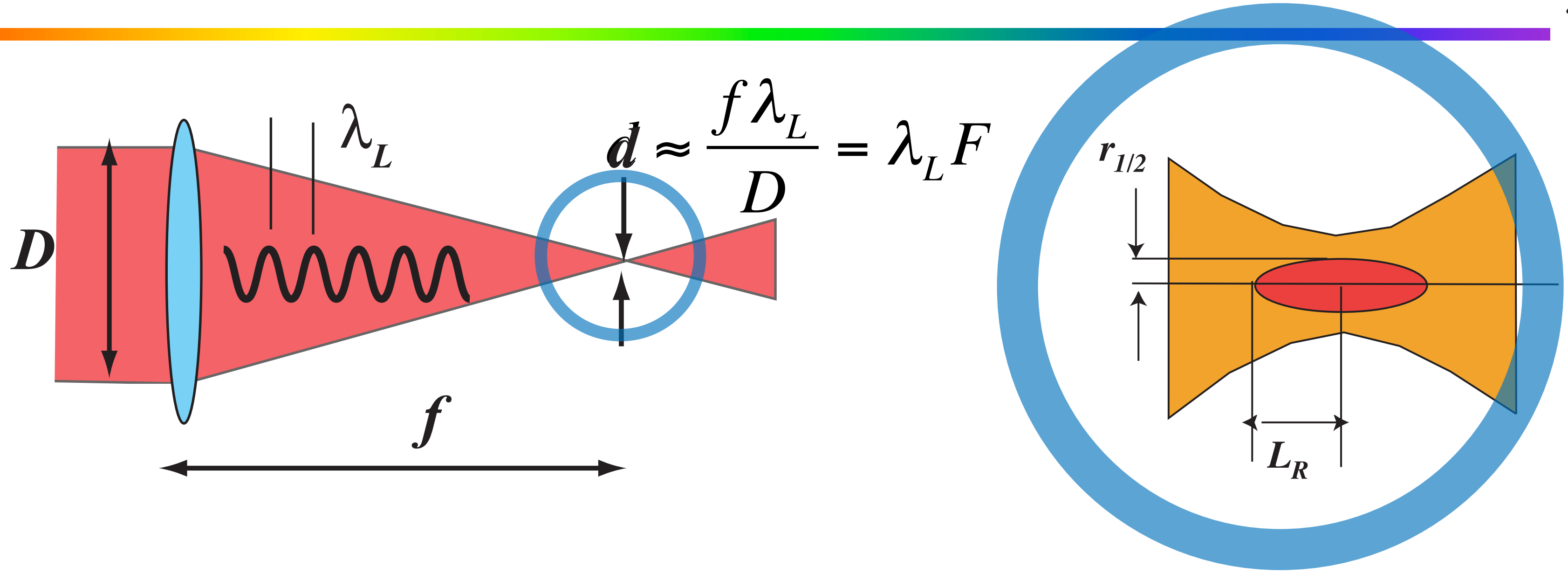

Rayleigh length $L_R = \frac{\pi w_0^2}{\lambda_0}$ $w_0 = r_{1/2} / \sqrt{\ln 2/2} \approx 1.7\, r_{1/2}$

Dephasing length $L_{dp} = c\pi \frac{\gamma_\phi^2}{\omega_p}$

- * The focal spot diameter and the Rayleigh range are increased (≈2 times).
- * In order to keep the relativistic intensity of the laser (>10^{18}W/cm^2), the laser power should be increased from 2 TW to 3-4TW.
- * For elongate the dephasing length, the plasma density is decreased from 1.5X10^{20}cm^{-3} to (2-4)X10^{19}cm^{-3}.

Electron Density Dependence of Electron Energy Spectra

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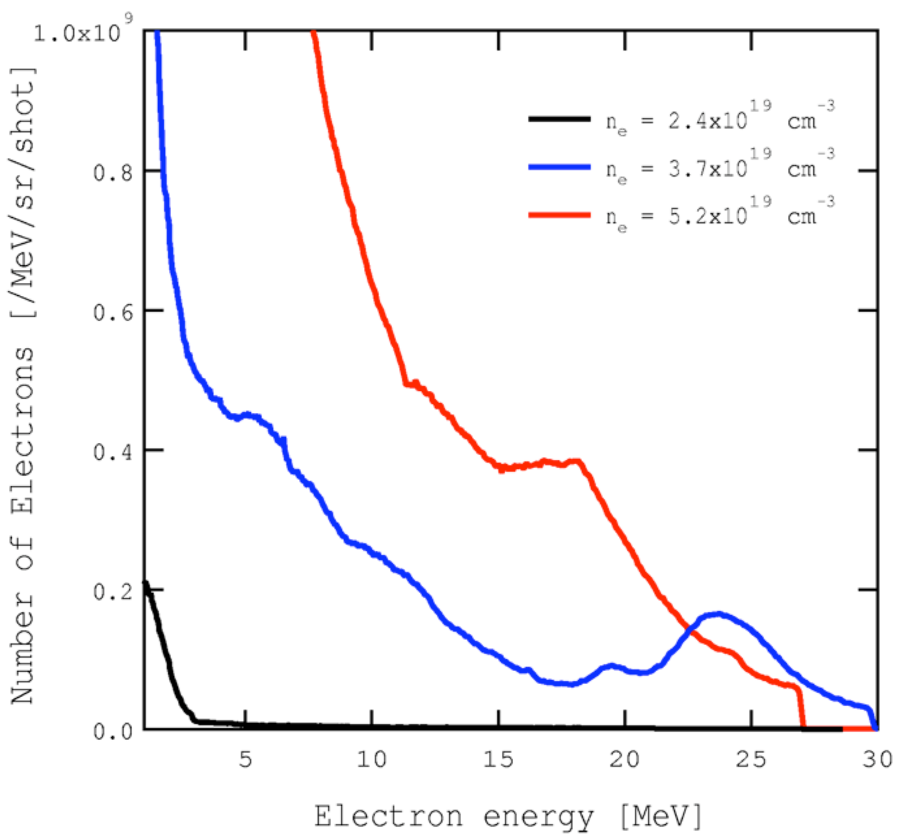
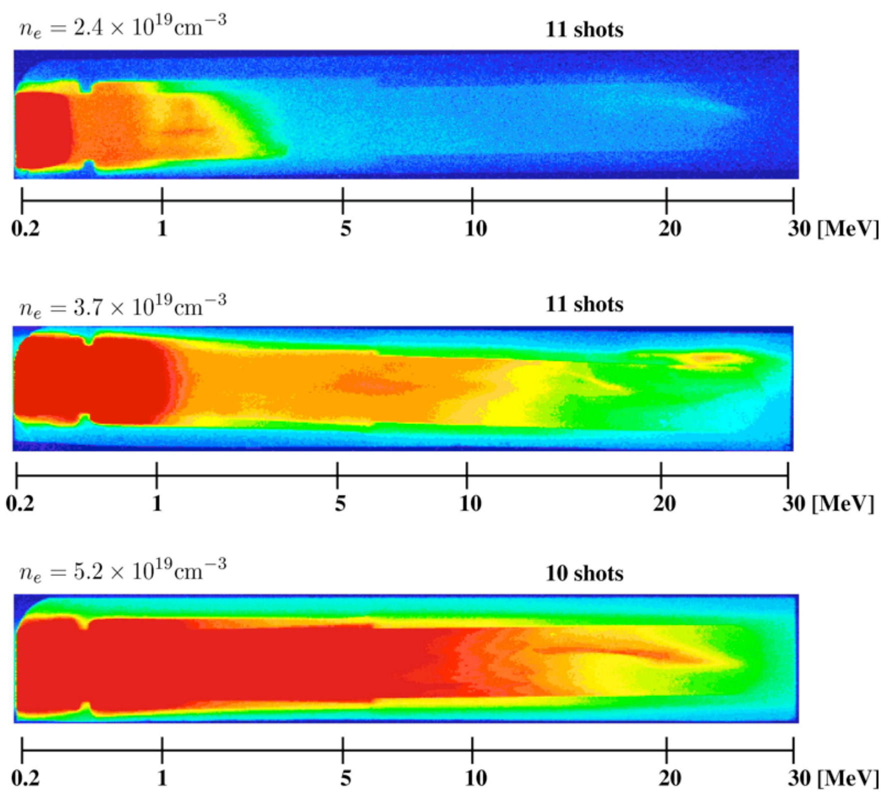
2.7 TW





The monoenergetic peak with the energy of 18-25MeV was observed at ne = (4~5)x10^{19} cm^{-3}.
The number of electrons is 4 x10^5 / shot in a peak.
The divergence of the monoenergetic electron bunch is estimated at 20 mrad.

Single-shot Energy Spectrum of Electron Beam

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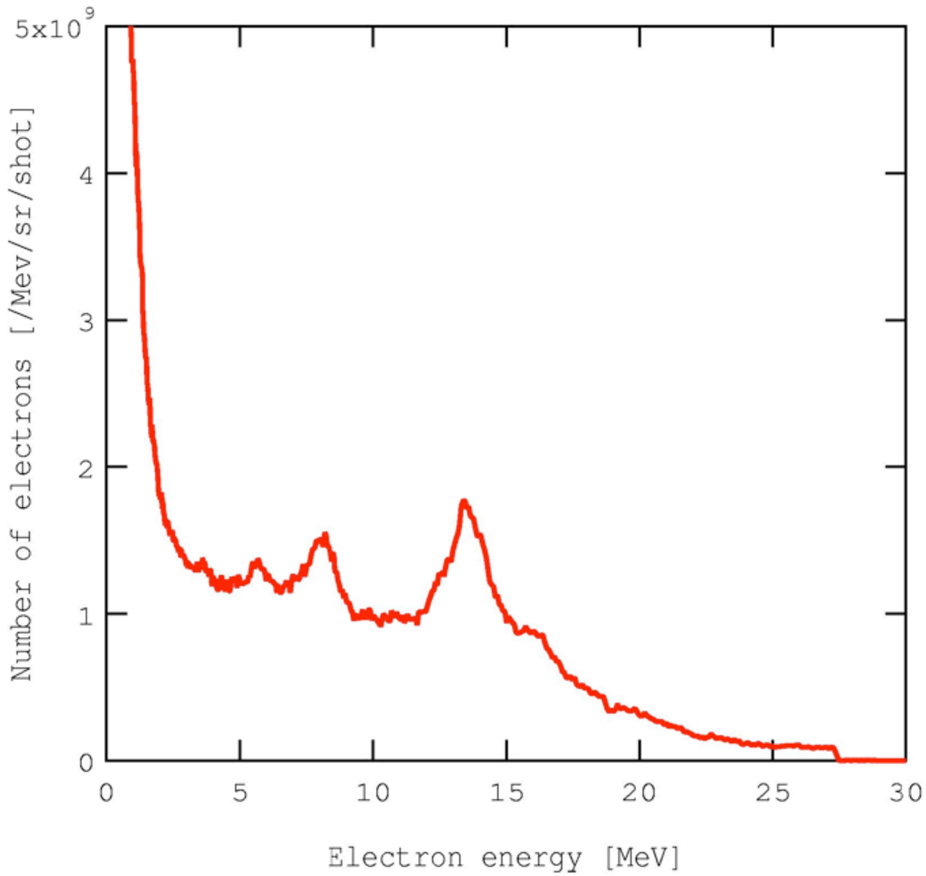

$P_L = 3.8$ TW

$n_e = 3.2\times10^{19}\mathrm{cm}^{-3}$

* A few monoenergetic components are observed by the single shot measurement.
* This might be caused by the excitation of a few potential wells, which are responsible for the electron acceleration.

* Number of electrons within the monoenergetic peaks are more than 10^6.

Single-shot Spectrum of Forward-scattering of laser

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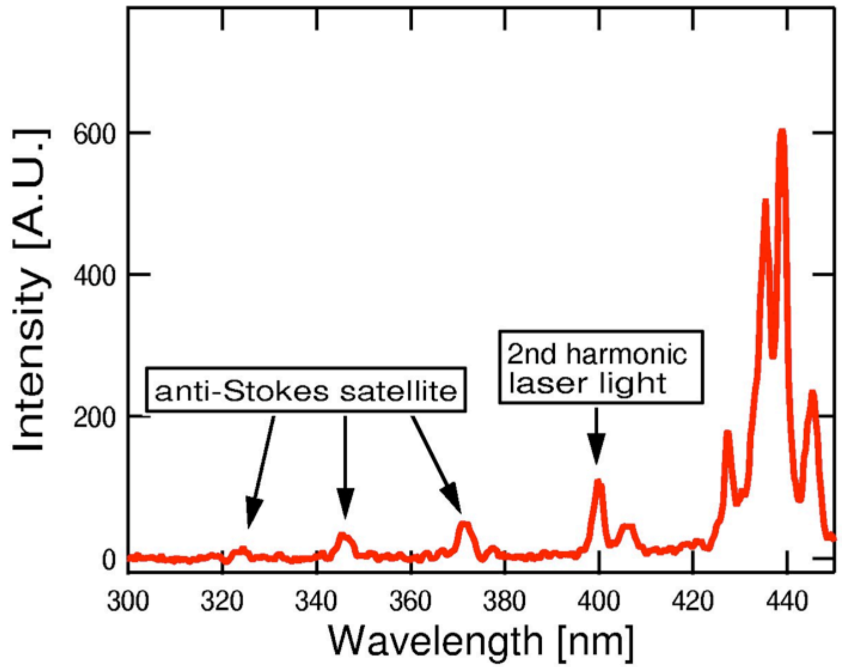
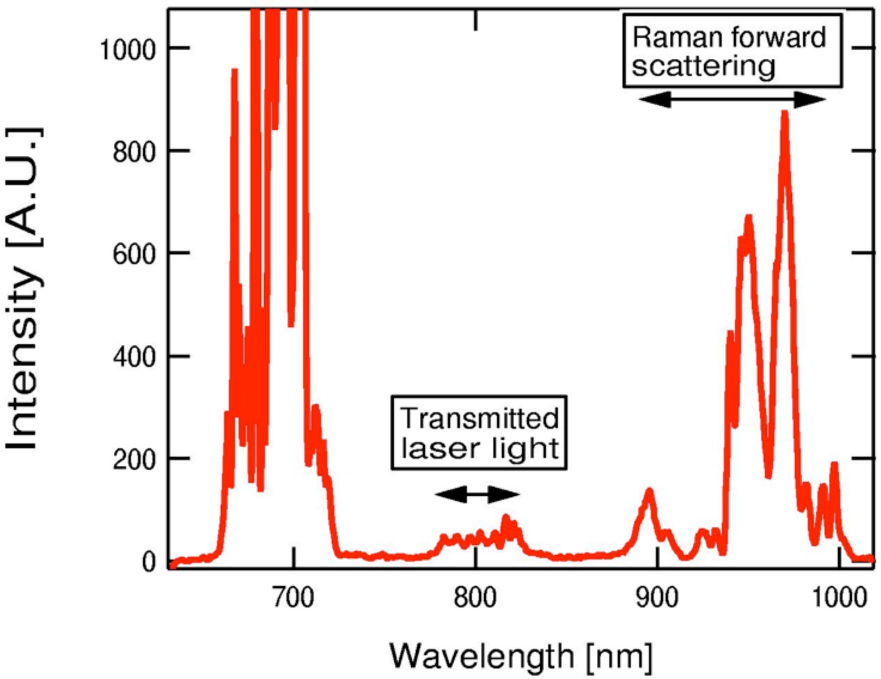
$P_L = 3.8$ TW

$n_e = 3.2 \times 10^{19} \text{cm}^{-3}$





The second harmonic laser light was observed for the laser power higher than 3TW.
The plasma electron density estimated from the the Stokes satellite peaks is agree with the gas jet density measurement.
The density modulation is 60-80％.

Energy gain of monoenergetic electrons at the new setup

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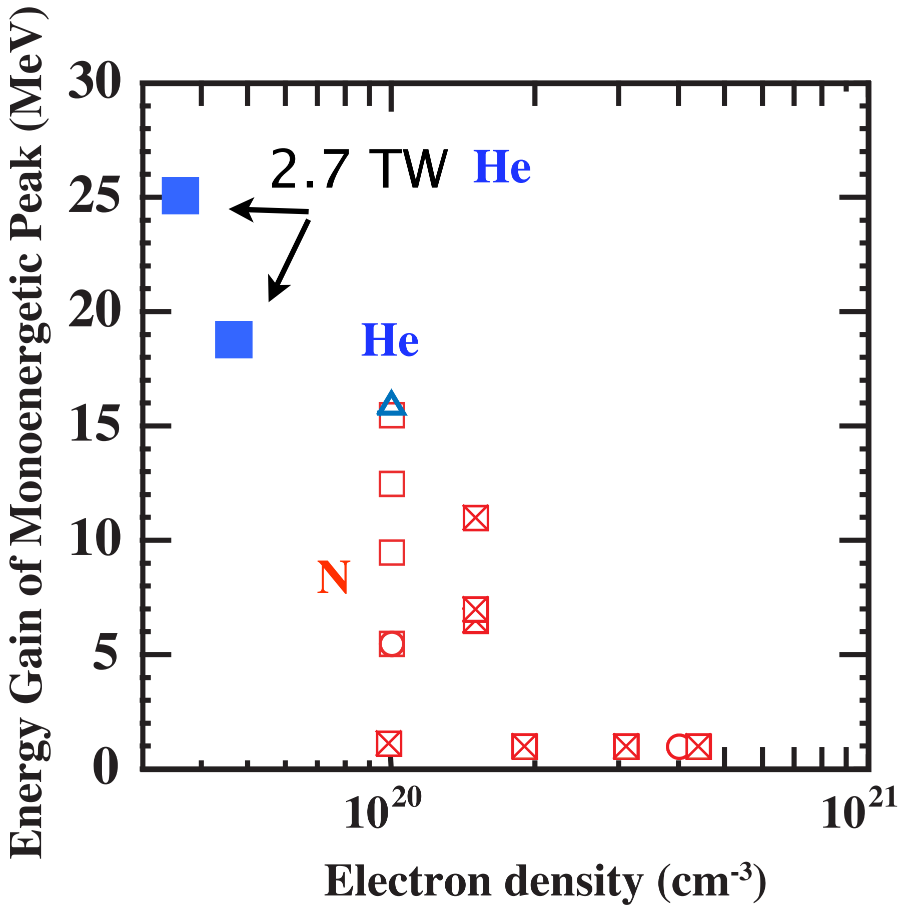

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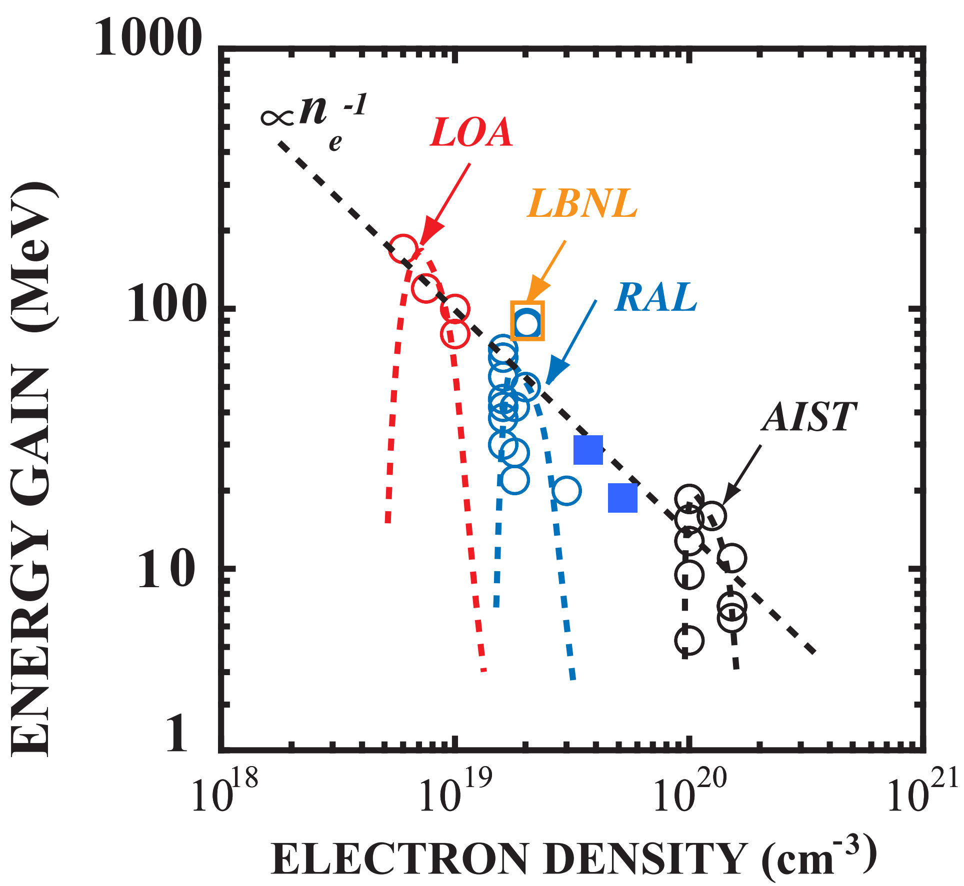
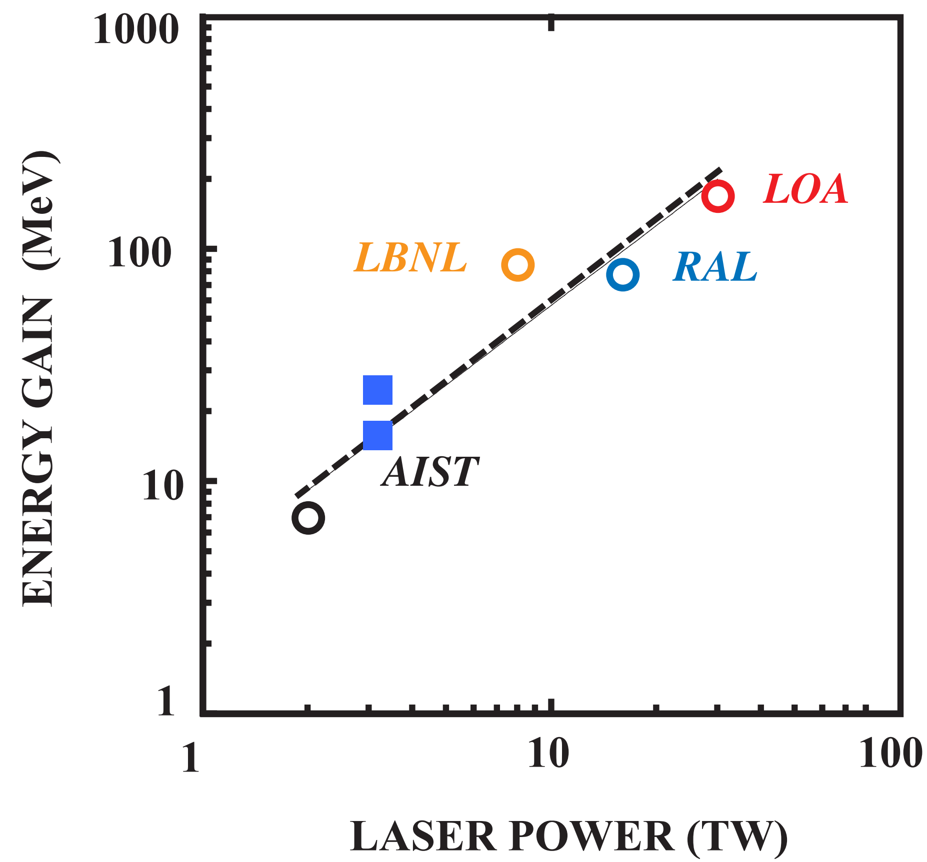
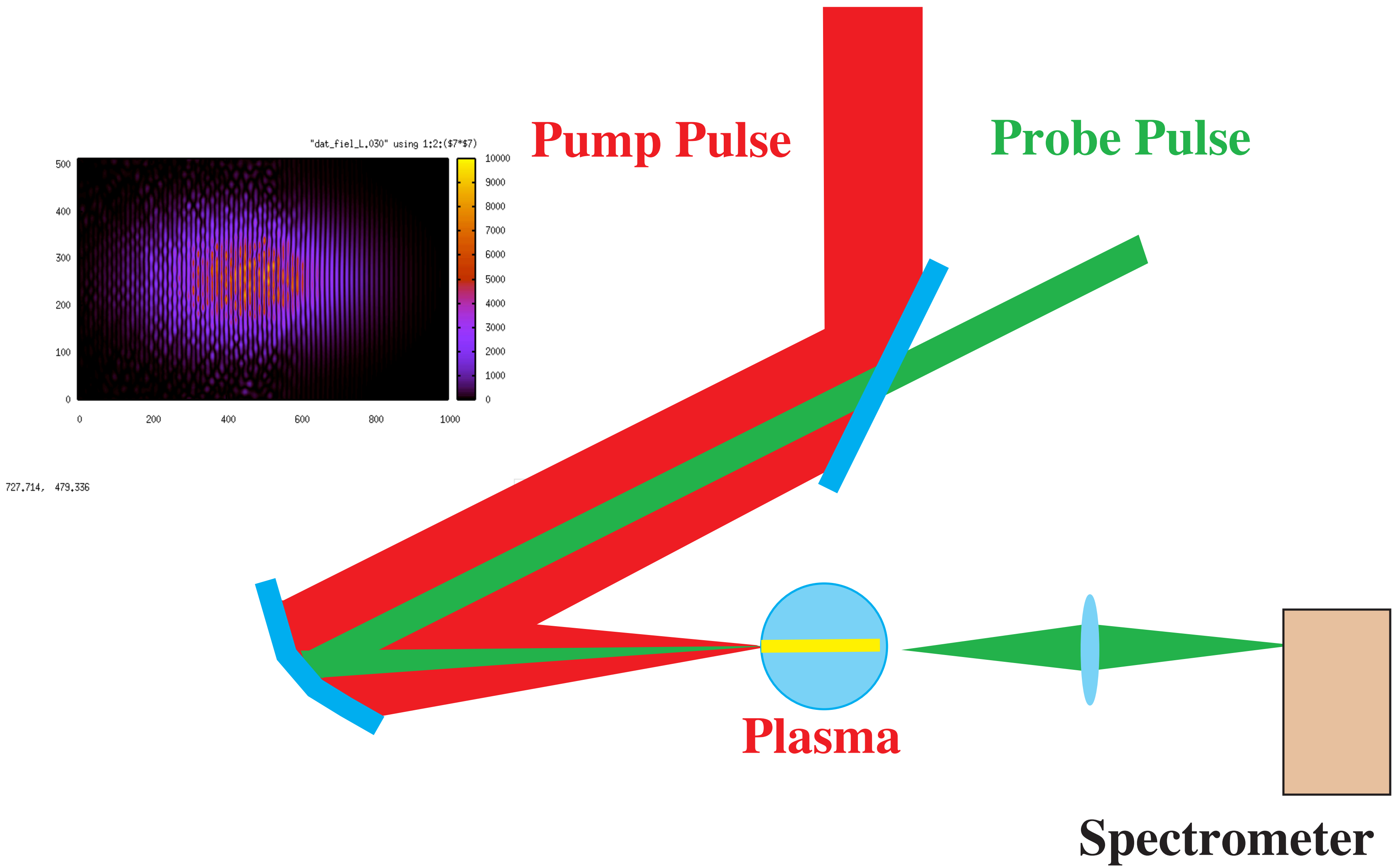




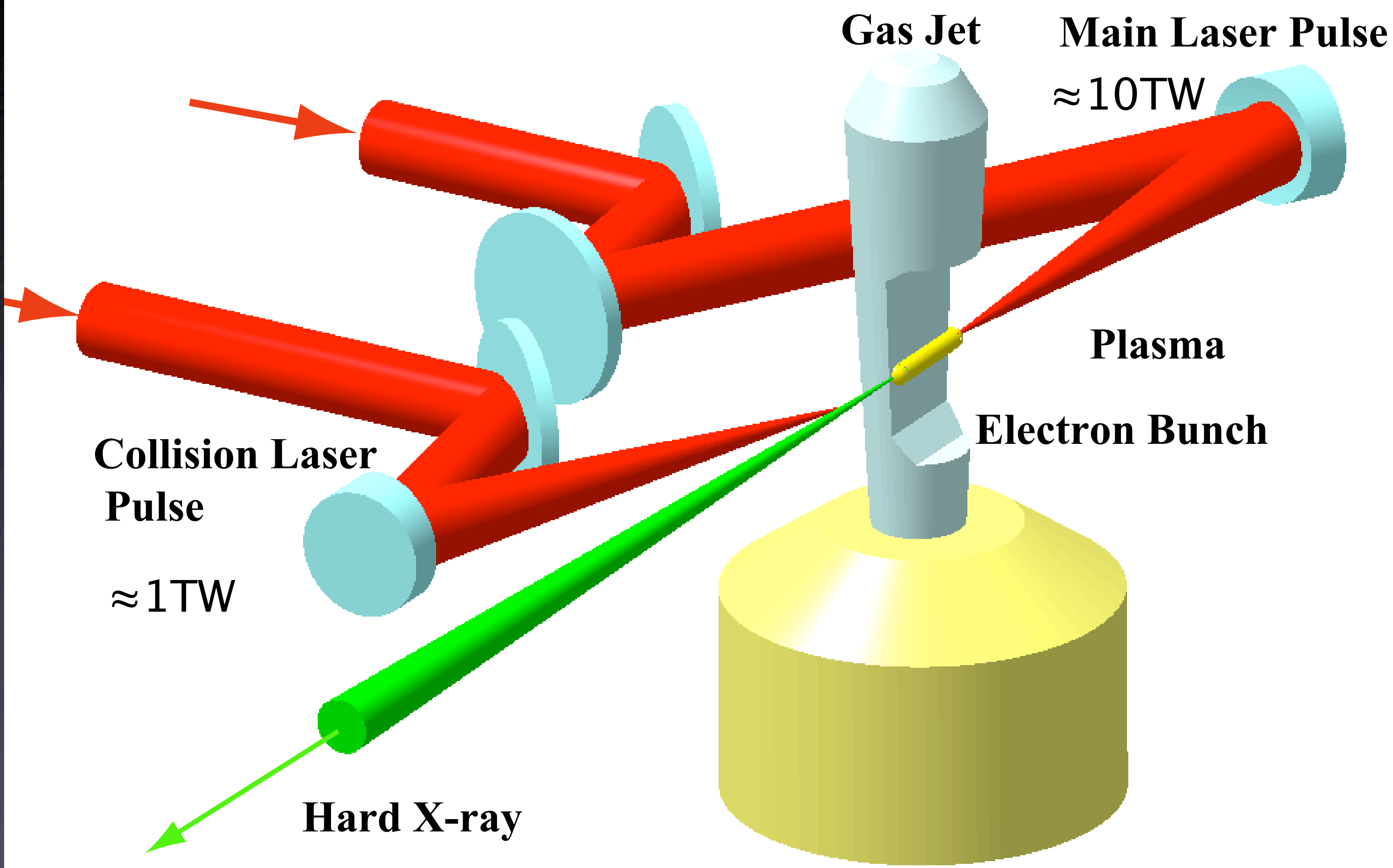
$$\tilde{W}_{\max} = \eta \cdot \frac{\pi}{\pi \tilde{r}_L^2} \tilde{n}_e^{-1} \tilde{P} \gamma_\perp^2$$

Plasma Diagnostics / Thomson scattering

To know the growth and dumping rate of the plasma wave.



Pulse X-ray Source by Inverse Compton Scattering



+ Improvement of reproducibility / stability

FY 2005-2009
at AIST

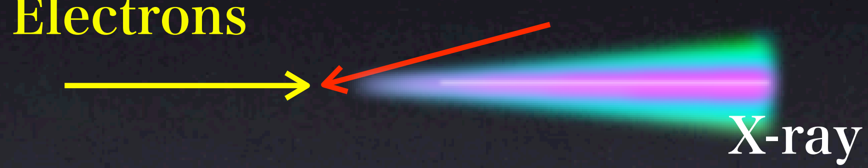
Estimation of the X-ray

$$E_X \approx \frac{4\gamma^2 E_L}{1+(\gamma\theta)^2 + 4\gamma E_L / m_e c^2} \approx \frac{4\gamma^2 E_L}{1+(\gamma\theta)^2}$$

$(\Psi = \pi, \quad \theta << 1)$

$$\sigma \approx \sigma_T \left\{ 1 - 2\frac{\gamma E_L}{m_e c^2} + \ldots\ldots\ldots\ldots \right\}, \quad \left(\gamma E_L << m_e c^2\right)$$

$$\sigma_T = 6.6 \times 10^{-25}\,\mathrm{cm}^2$$



$$N_x \approx \sigma_T c n_e n_L V \tau_L$$

$$\Delta\theta \approx 1/\gamma$$

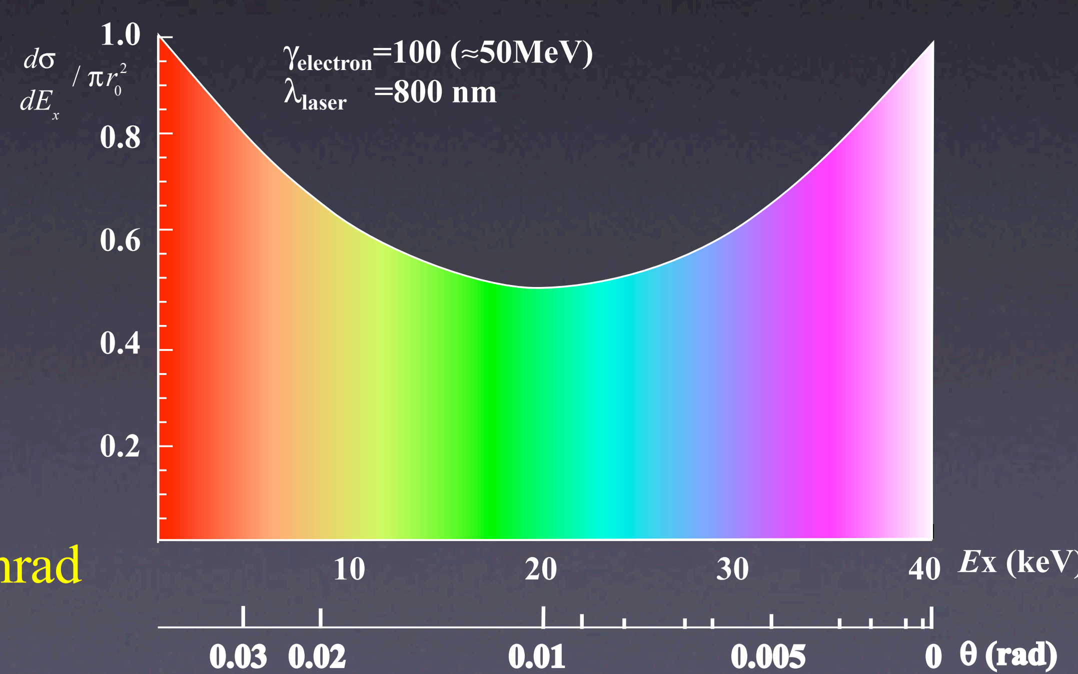
$$n_e \approx 1.3 \times 10^{17}\,\mathrm{cm}^{-3}; (N_e = 6 \times 10^8, V \approx \pi r^2 c \tau_L)$$

$$n_L \approx 1.3 \times 10^{25}\,\mathrm{cm}^{-3}; (I_L = 1 \times 10^{17}\,\mathrm{W/cm}^2)$$

$$V = 4.7 \times 10^{-9}\,\mathrm{cm}^3; (r = 10\mu\mathrm{m}, \tau_L = 50\mathrm{fs})$$

$$\Rightarrow N_x \approx 7.7 \times 10^6\,\mathrm{photons/5mrad} \approx 370\,\mathrm{ergs/5mrad}$$

$$1\,\mathrm{erg/cm}^2 \Rightarrow 20\mathrm{cm}\Phi \text{ at } 20\mathrm{m}$$



Conclusion

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- **Monoenergetic electron beams were obtained by the laser-plasma particle acceleration.**

- **The energy gain is approximately proportional to P/n_e, however the density range is limited for the fixed laser power.**

- **The normalized emittance of the beam were less than 1 π mm mrad.**

- **The Stokes satellite peak in the forward scattering shows that the monoenergetic beam was accelerated by the self-modulated wakefield.**