ICFA Workshop on Compton Sources for X/γ Rays: Physics and Applications

Porto Conte, Sardinia, Italy

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Laser-plasma electron accelerator for all optical inverse-Compton x-ray source

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OUTLINE

- ALL OPTICAL INVERSE-COMPTON X-RAY SOURCES
- LASER-PLASMA ELECTRON ACCELERATORS

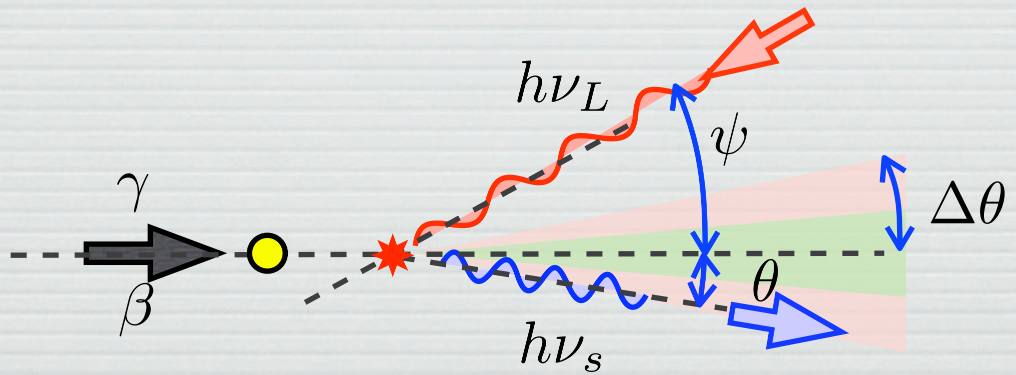
  (WAKEFIELD ACCELERATORS)

  PRINCIPLE AND CHARACTERISTICS

- STABILIZATION OF WAKE-FIELD ACCELERATORS

Inverse Compton x-ray source

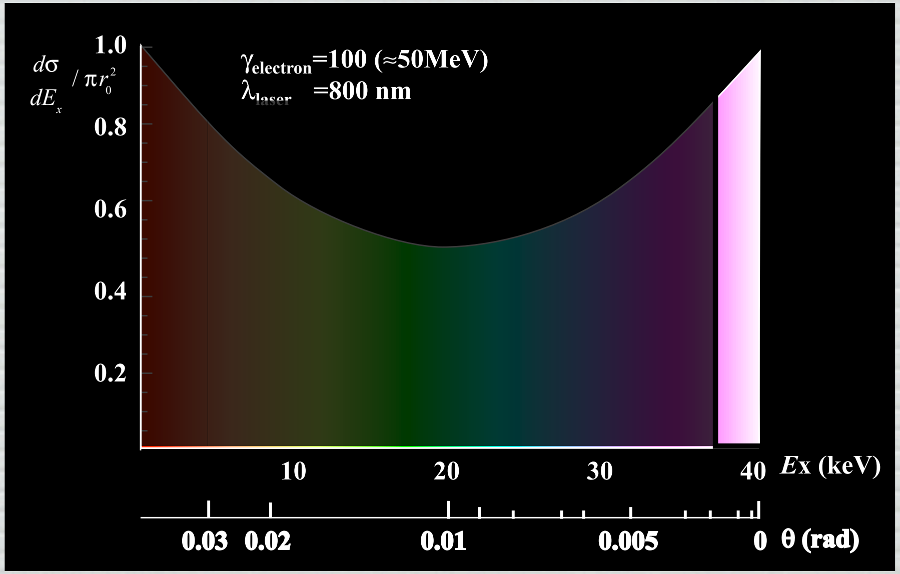
Inverse Compton scattering provides a monochromatic x-ray pulse by Doppler upshifting of an intense laser pulse.



$$h\nu_s \simeq h\nu_L \frac{2\gamma^2 (1 + \beta \cos\psi)}{1 + (\gamma\theta)^2}$$

$$h\nu \ll mc^2,\ \theta \ll 1,\ a_0 \ll 1$$

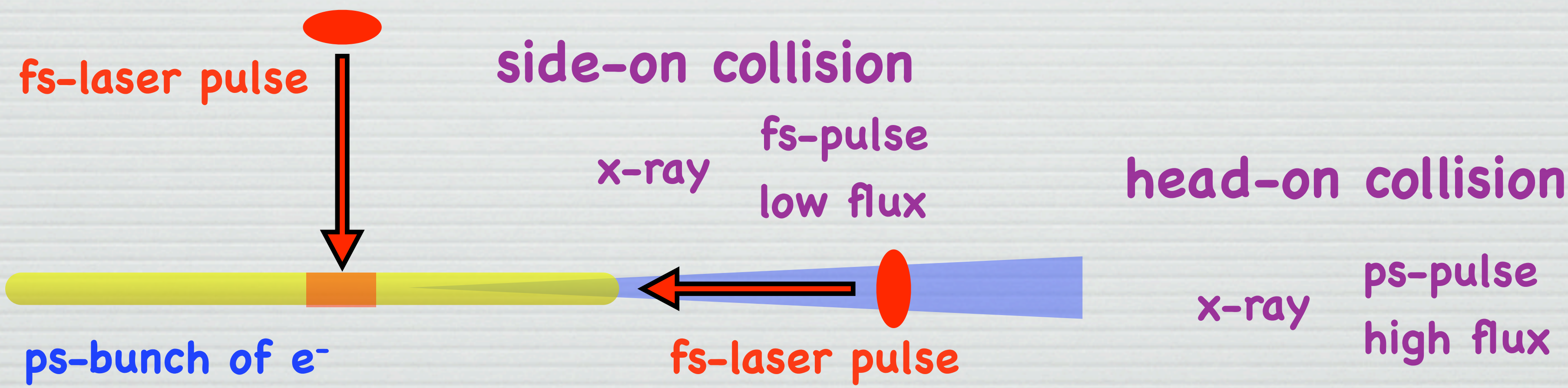
$$\Delta\theta = 1/\gamma$$



Inverse Compton x-ray source II

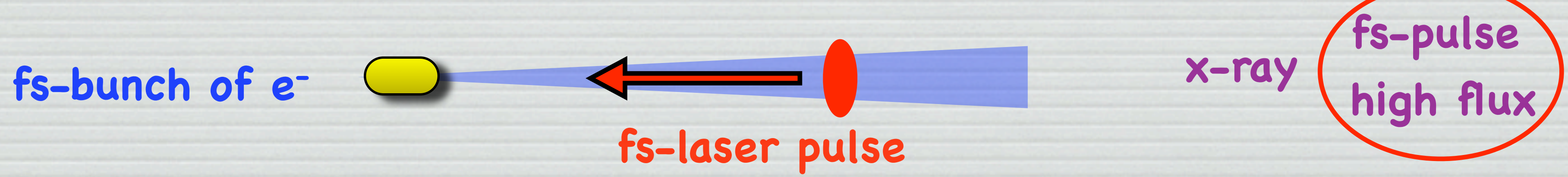
Duration of x-ray pulse $\propto$ e^--bunch length + laser pulse

Intensity of x-ray pulse $\propto$ number of interaction e^- $\times$ $h\nu$-density



Laser wakefield accelerator can deliver a sub-nC, fs-bunch of e^-.

head-on collision



Inverse Compton x-ray source III

≈ 10^7 X-ray photons per shot

≈ 100pC, 10^{17} W/cm^2, 5x10^{-9}cm^3

to produce a few-MeV photons (@ 1eV)

$$h\nu_s \simeq 4\gamma^2 \cdot h\nu_L, \quad (\psi \approx 0, \theta \approx 0)$$

0.4~0.5GeV

	Accel. gradient	Length for 500MeV
rf-linac	10-40 MeV/m	≈ 25~50 m
LWFA	96 GeV/m	≈5 mm

Laser wakefield electron accelerator

1. Electrons are expelled by the laser pulse.

   ponderomotive force

$$\mathbf{f}_{NL} = -\frac{e^2}{4m\omega^2}\nabla E_s^2$$

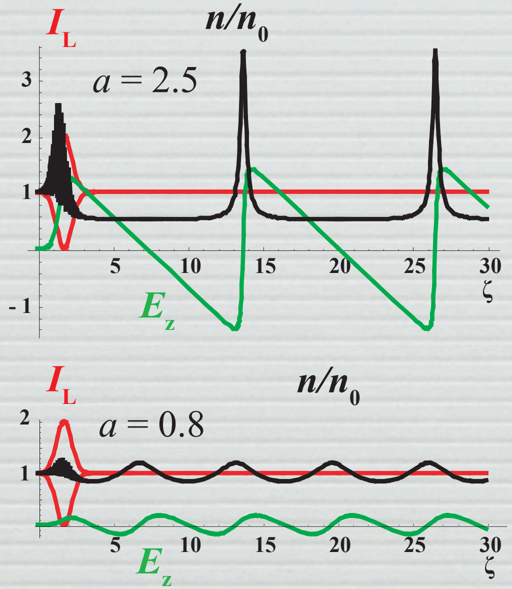
2. Displaced electrons are pulled back by the Coulomb force.

   plasma wave is excited behind the laser pulse (wakefield)

   traveling at the speed of light

$$\left(\frac{\partial^2}{\partial t^2} + \omega_{pe}^2\right)\phi = \frac{mc^2}{4e}\omega_{pe}^2 a^2$$

3. Electrons riding the wakefield are accelerated.



$$E_{WB}/E_0 = \left[2\left(\gamma_{ph} - 1\right)\right]^{1/2}$$

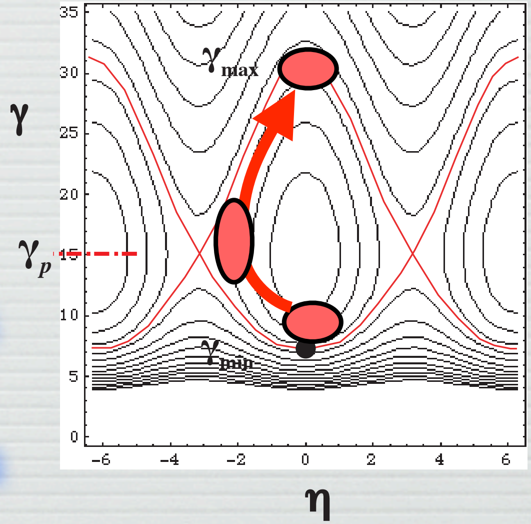
$$E_0 = cm\omega_{pe}/e$$

$$E_0 = 96 \text{ GV/m} \quad \text{for } n_e = 10^{18}\text{cm}^{-3}$$

K.Koyama ; ICFA Workshop on *Compton Sources for X/γ Rays: Physics and Applications,* Alghero, Italy 2008

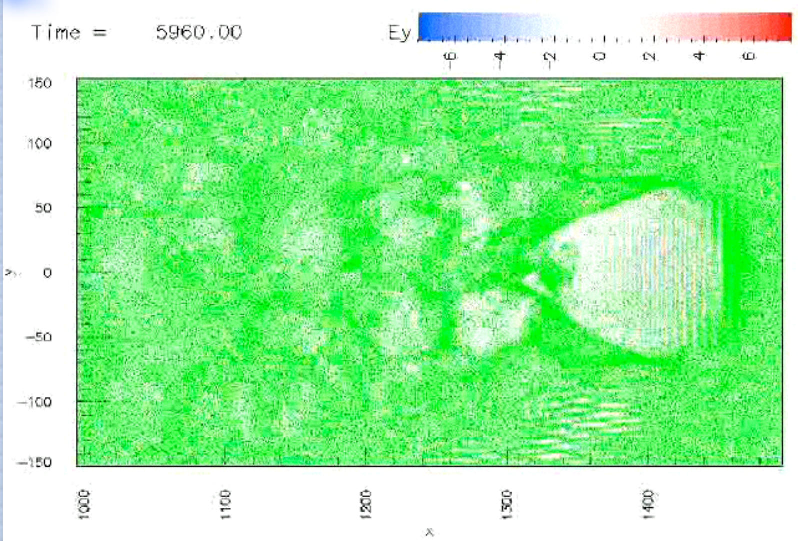
Mono-energetic electron acceleration

1. **Electrons should be accelerated by a single well.**
   - excitation of single well
   - electron injection to one of wells

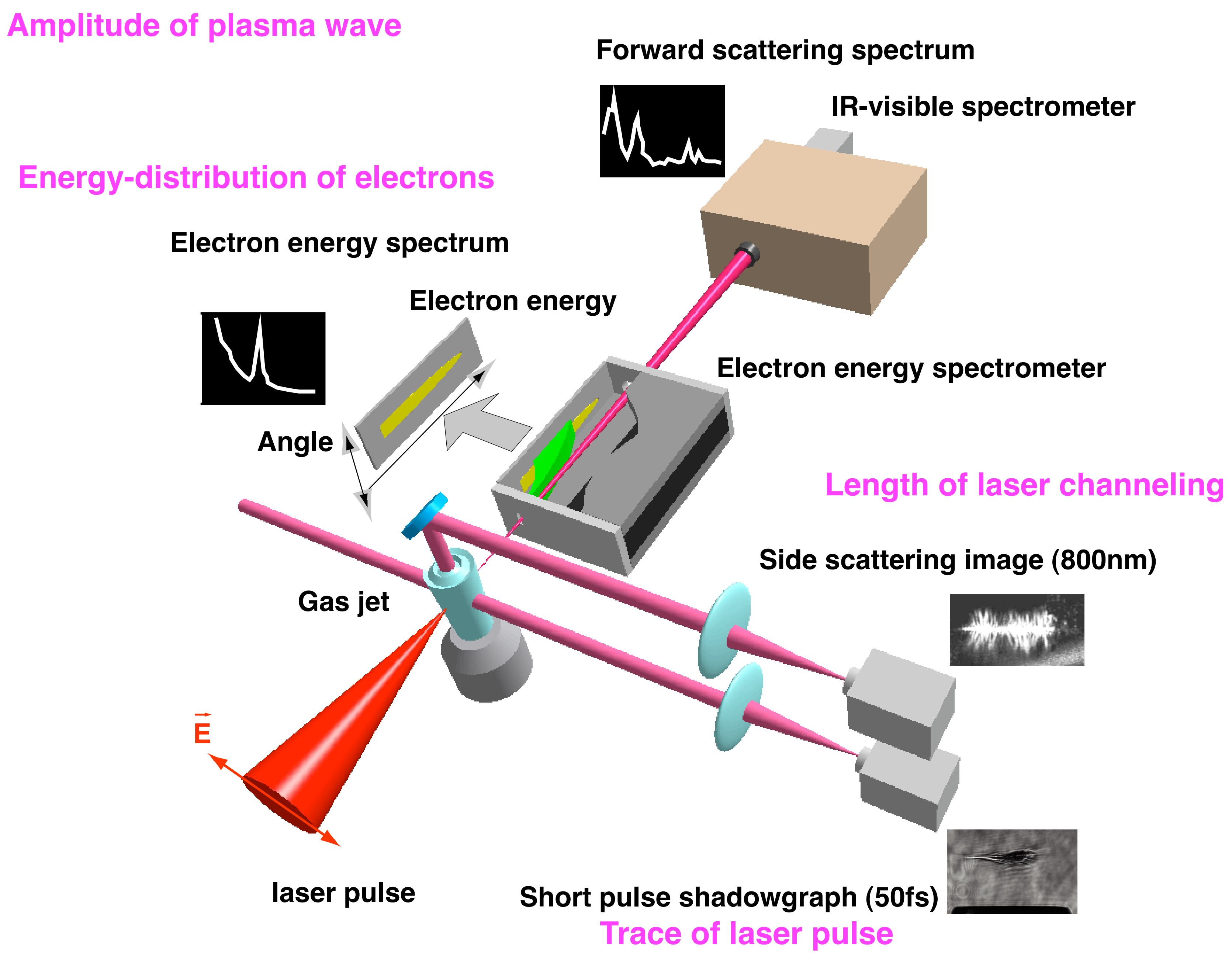


2. **Initial electrons must be injected in a small portion of the phase space.**
   - self-trapping
   - external injection

3. **Acceleration length**
   ≈ dephasing length



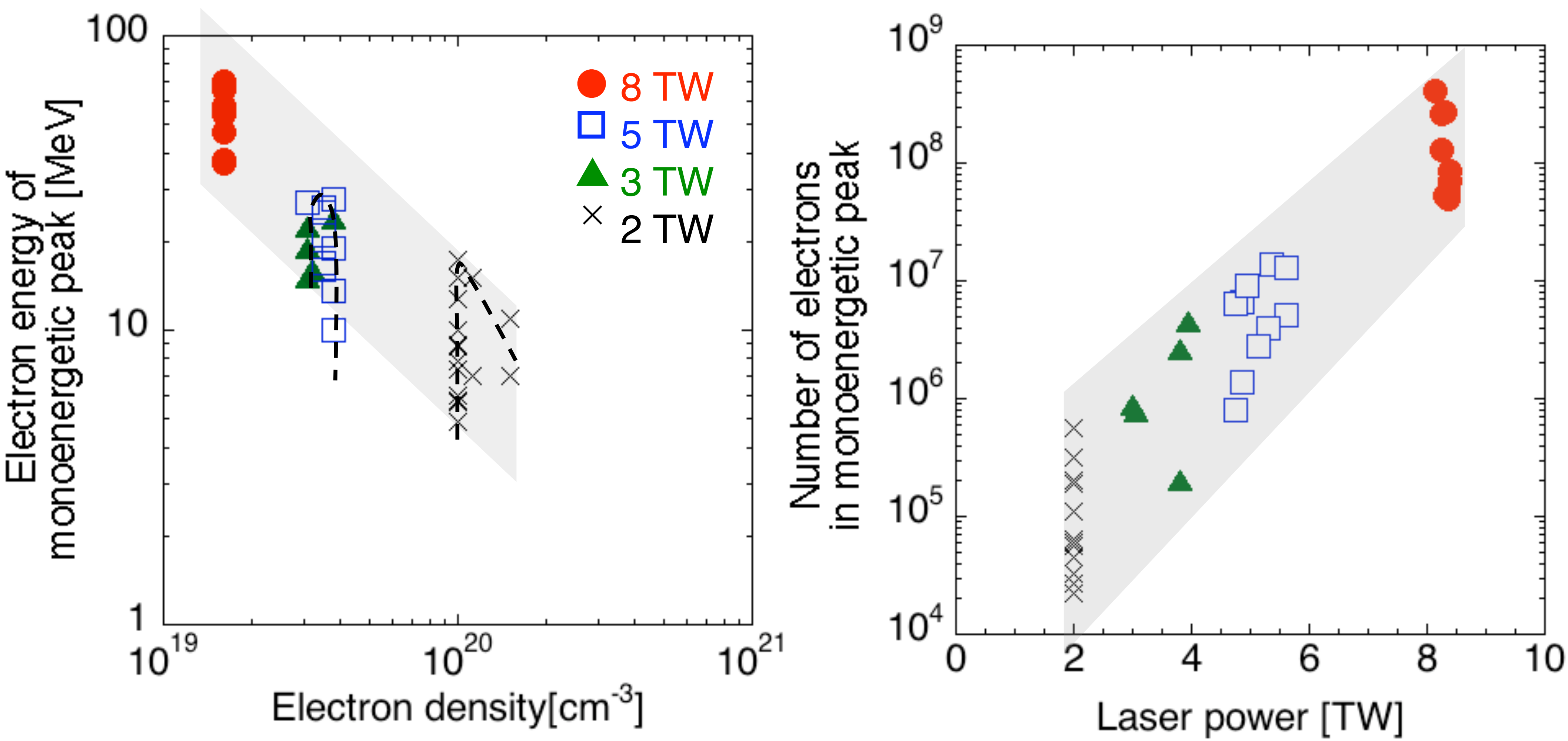
Schematic drawing of experimental setup



Recent activities of LWFA experiments at AIST and U.Tokyo

- ☑ Empirical scaling law of LWFA.
- ☑ Electron injection at a density step.
  - density jump formation by the shock wave
- ☑ Axial magnetic to stabilize LWFA.
  - deep capillary formation by the expanding shock in B-field
  - electron injection and post acceleration
  - ≈ 0.5 GeV by 8 TW laser pulse

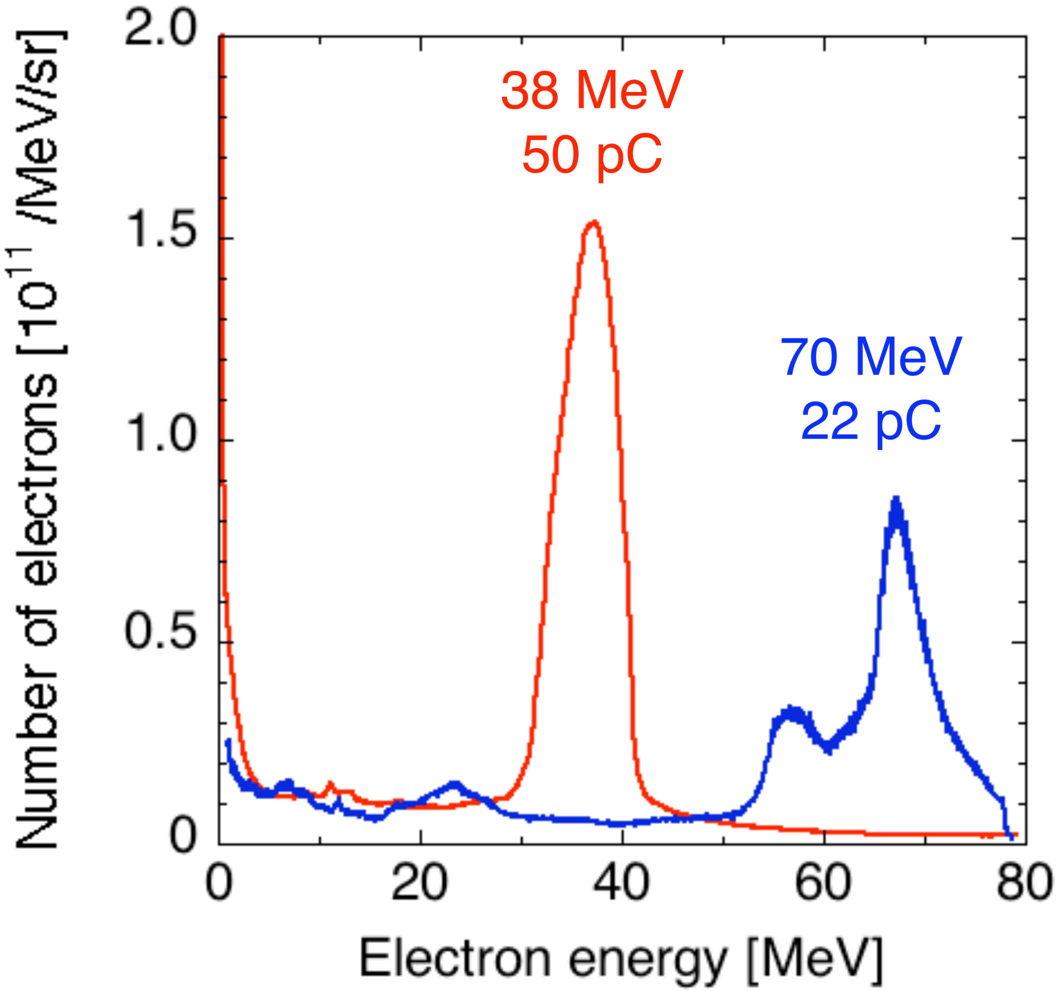
Scaling and achieved parameters in quasi-monoenergetic electron beam generation



(by courtesy of E. Miura, AIST)

Stable generation of quasi-monoenergetic electron beam by self-injection scheme

Laser : 8.5 TW / 50 fs
Electron density : $1.6 \times 10^{19}\ cm^{-3}$



Statistics of quasi-monoenergetic beams in consecutive 20 shots

Parameters	Mean (± s.d.)
Peak energy	55 ± 16 MeV
Energy spread ($\Delta E_{FWHM}/E$)	21 ± 11 %
Charge in peak	15 ± 10 pC
Beam divergence (FWHM)	7.6 ± 3.5 mrad
Beam pointing	± 7.6 mrad
Probability of generation	80%

(by courtesy of E. Miura, AIST)

For increasing stability

Energy

Energy width

Electronic charge

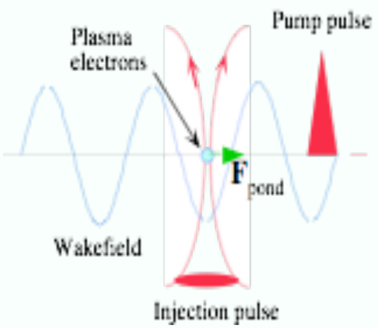
Emittance

Beam pointing

- ☑ Amplitude of the wakefield
- ☑ External injection of initial electrons
- ☑ Acceleration-length
- ☑ Laser guiding

Electron injections

Locally increased ponderomotive force produced by colliding laser pulses

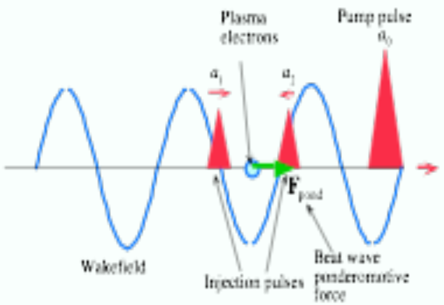


The laser pulse crosses the wakefield

D.Umstadter *et al*., Phys. Rev. Lett. **76**, 2073 (1996).

Beatwave injection

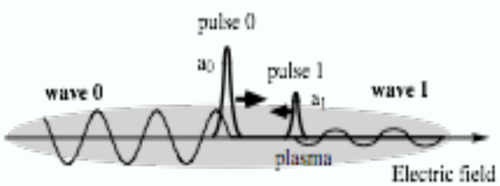
E. Esarey *et al*., Phys. Rev. Lett. **79**, 2683 (1997).



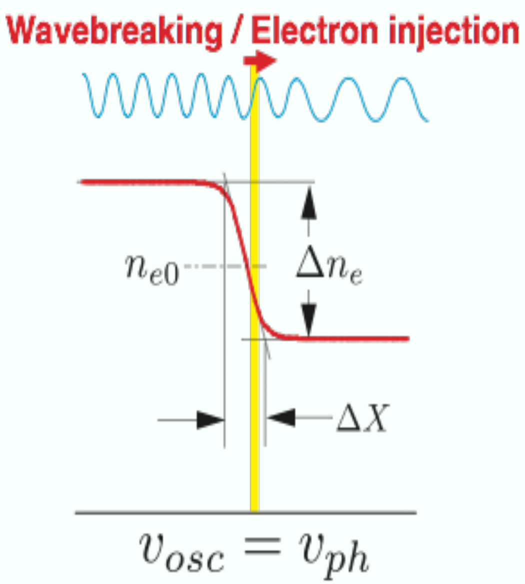
Standing wave

H. Kotaki *et al*., Phys. Plasmas **11**, 3296 (2004).

J. Faure *et al*., Nature **444**,737 (2006).



Local wavebreaking at the density ramp



S. V. Bulanov., Plasma Phys. Rep. **25**, 468 (1999).

T. Hosokai *et al*., Phys. Rev.E.**67**, 036407 (2003).

Wavebreaking at the density ramp

- The local wave number of the plasma wave, which propagate from high-density to low-density, i.e. from large ω_{pe} to small ω_{pe}, increases in time.

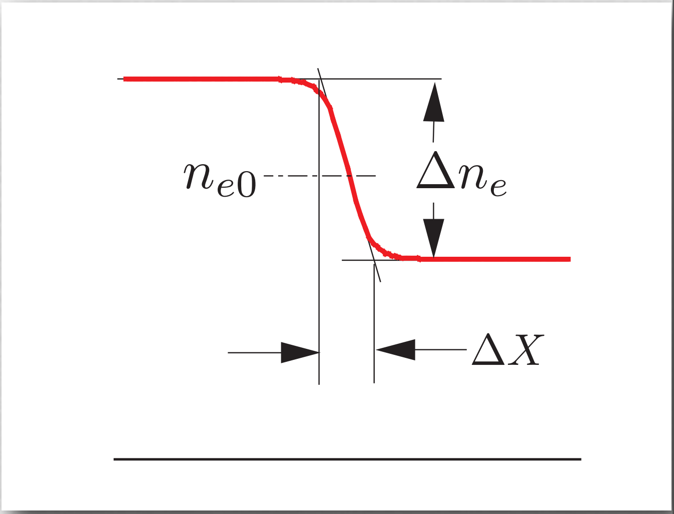
$$\frac{\partial}{\partial t} k_{pe}(t,z) = -\frac{\partial}{\partial z}\omega_{pe}(t,z)$$

- The phase velocity of the plasma wave $v_{ph} = \omega_{pe}/k_{pe}$ decreases.

- When the phase velocity is equal to the quivering velocity of the plasma wave v_q , the portion of the wave breaks.

$$v_q = \xi_m \omega_{pe} \sin(k_{pe} z_0 - \omega_{pe} t)$$

$$\boxed{k_{pe}\xi_m = 1 \quad (v_{ph} = v_q \qquad)}$$



The wave breaking occurs at the density discontinuity of the plasma.

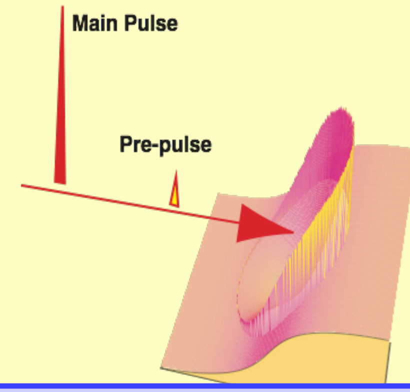
The density of injected electron. $n_{inj} \approx n_{e0}\frac{\xi_m}{\Delta X} = n_{e0}\frac{1}{k\Delta X}$

S. Bulanov, *et al.*, Phys. Rev. E 58, R5257 (1998).
P. Tomassini, *et al.*, Phys. Rev. STAB 6, 121301 (2003).

Methods for producing density ramps in plasmas

Shock front of the laser heated cavity

T.Hosokai, *et al*., Phys. Rev. E **67**, 036407 (2003)



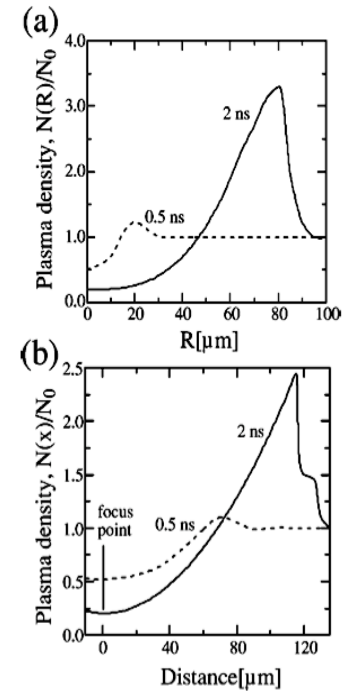
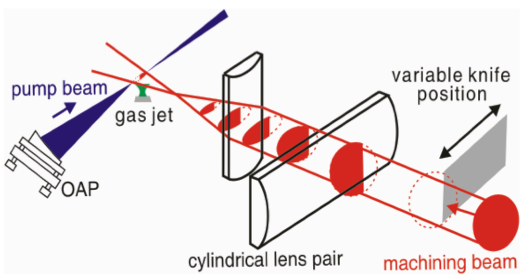


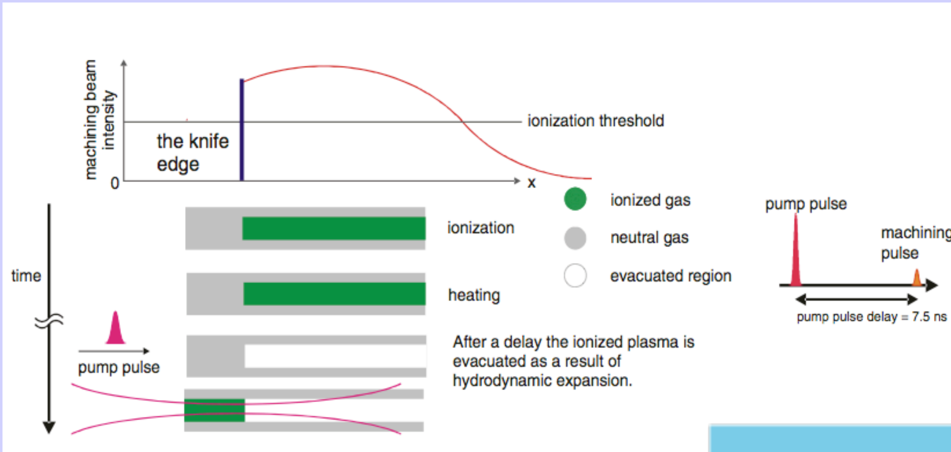
FIG. 6. Density distributions of a He jet after the laser prepulse calculated by 2D hydrodynamic simulation. The power density of the prepulse is 10^{13} W cm^{-2} and the Rayleigh length is 50 μm. (a) Radial direction ($x=0$), (b) longitudinal direction ($r=0$).

Laser machining of the plasma



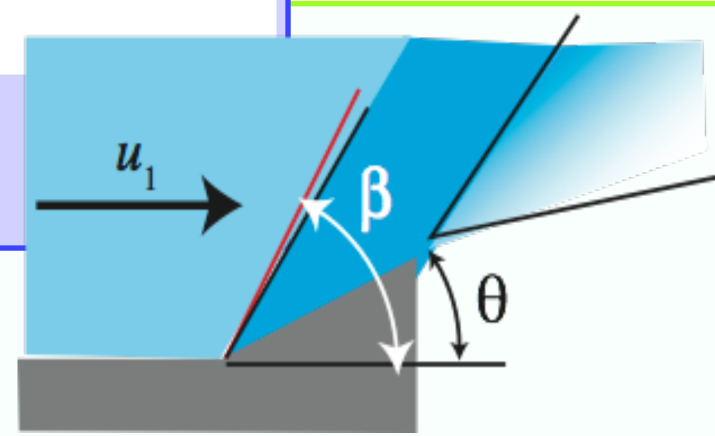
laser parameters:

	pump beam	machining beam
energy	230 mJ	60 mJ
pulse duration (FWHM)	45 fs	45 fs
beam size	40 mm	40 mm
focal spot (FWHM)	10 μm	20 μm x 1.3 mm



C.-T. Hsieh, *et al*., Physical Review Letters **96,** 095001 (2006)

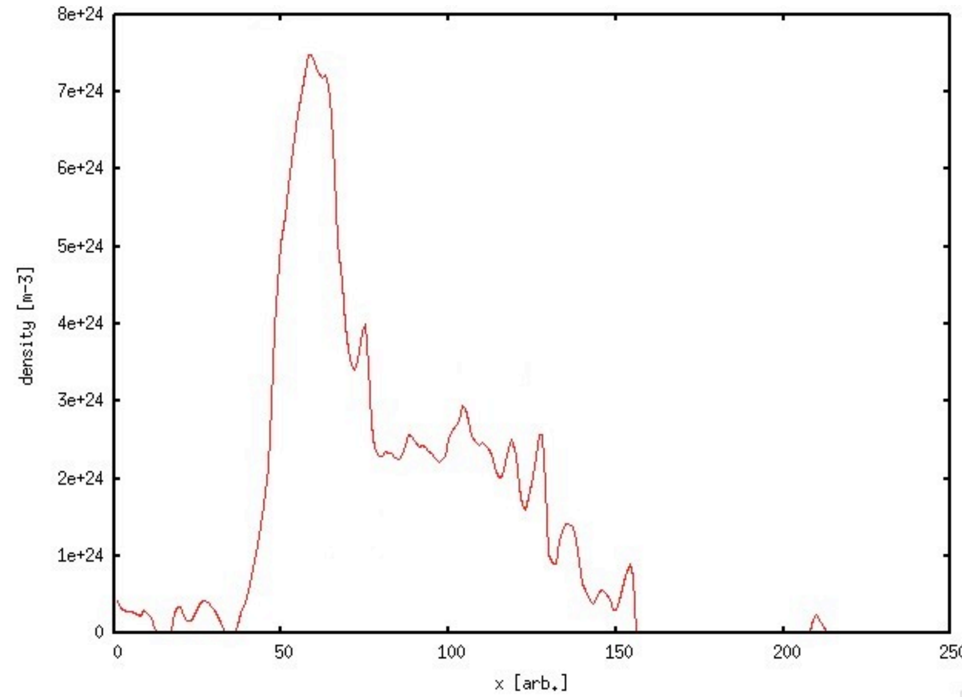
Oblique shock wave in a supersonic flow

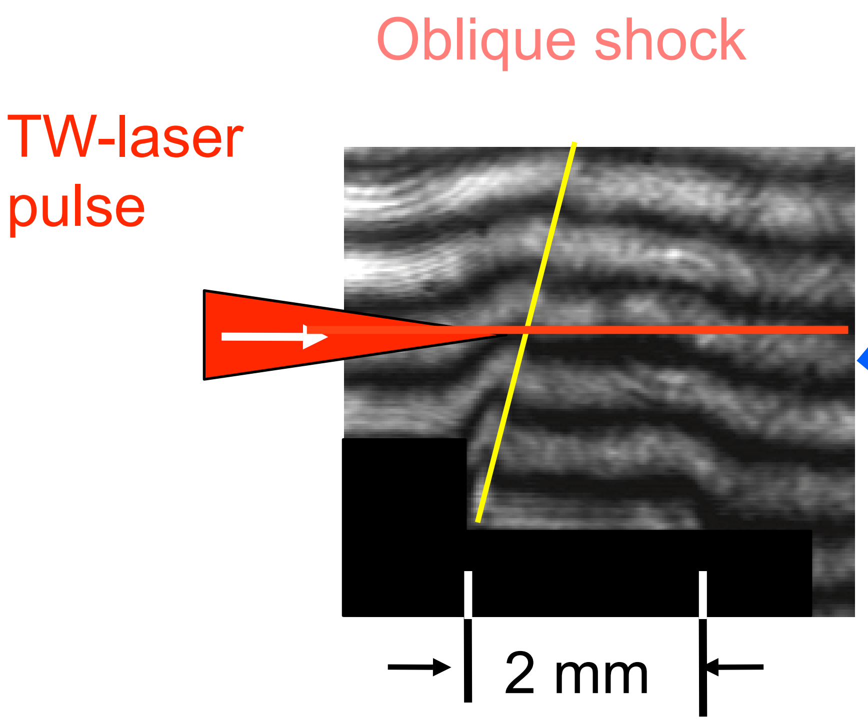


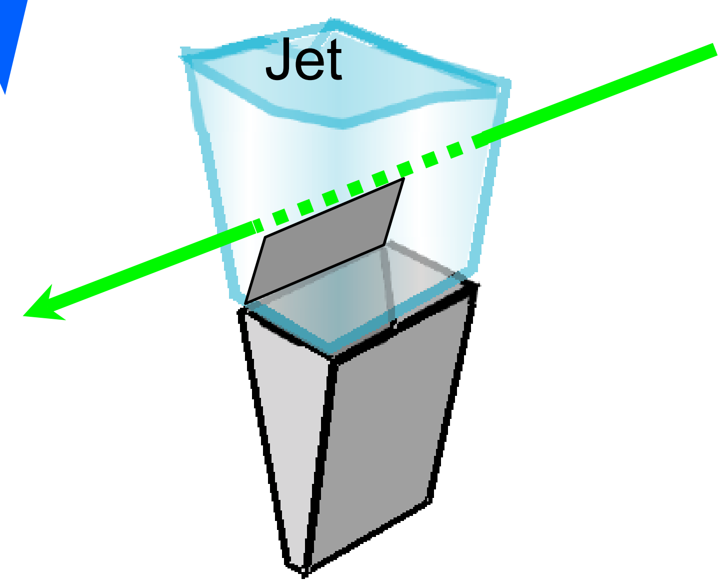
Density ramp formed by the oblique shock

The density ramp was produced by the oblique shock.

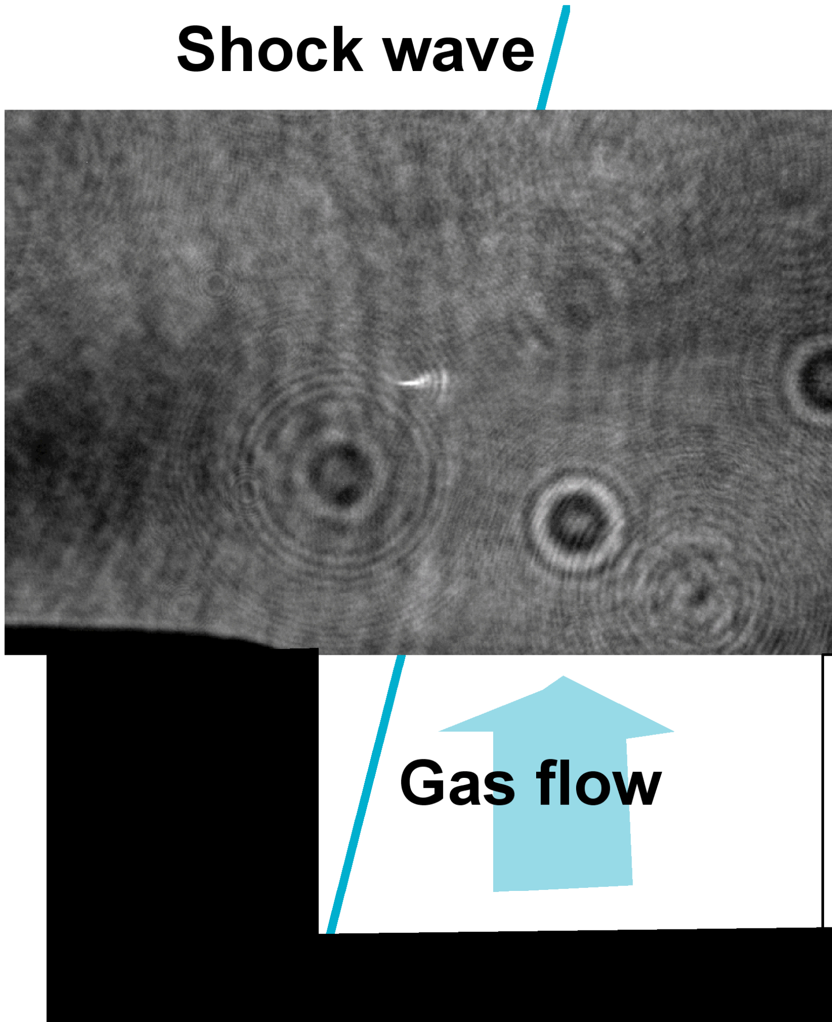
$n_2/n_1 \approx 3$, $L_n << 100\mu m$, $n_1 \approx 10^{19}$ cm^{-3}

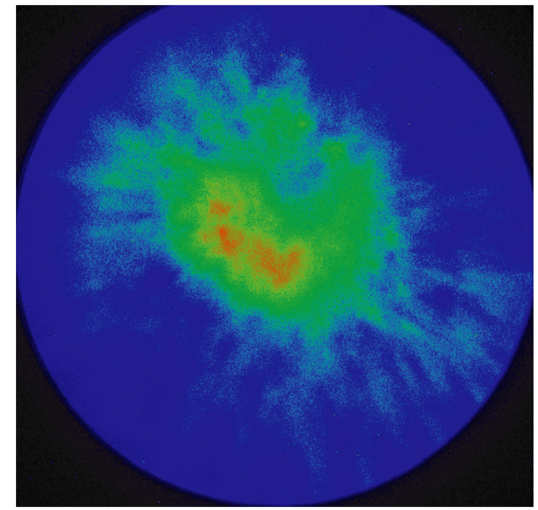


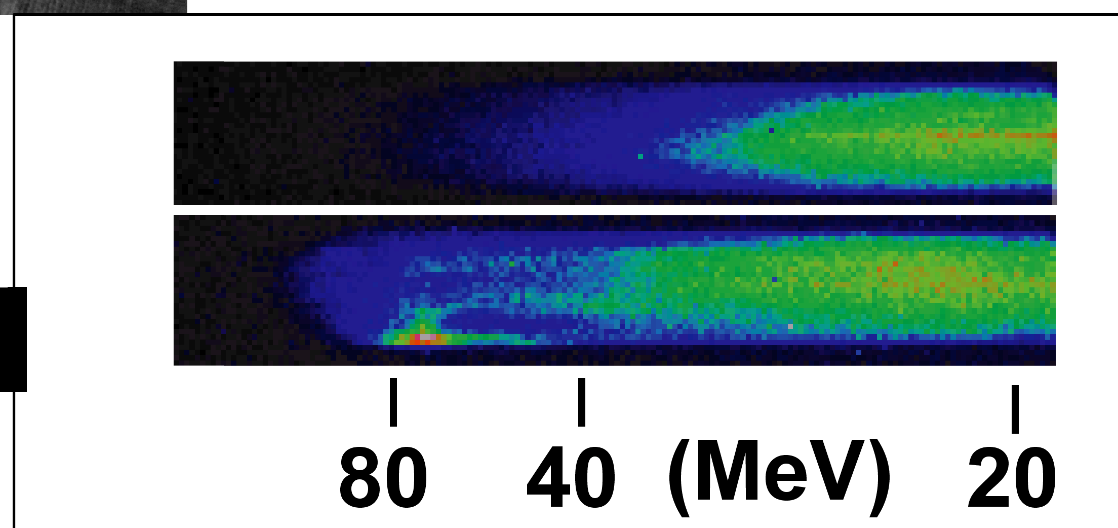




Preliminary result

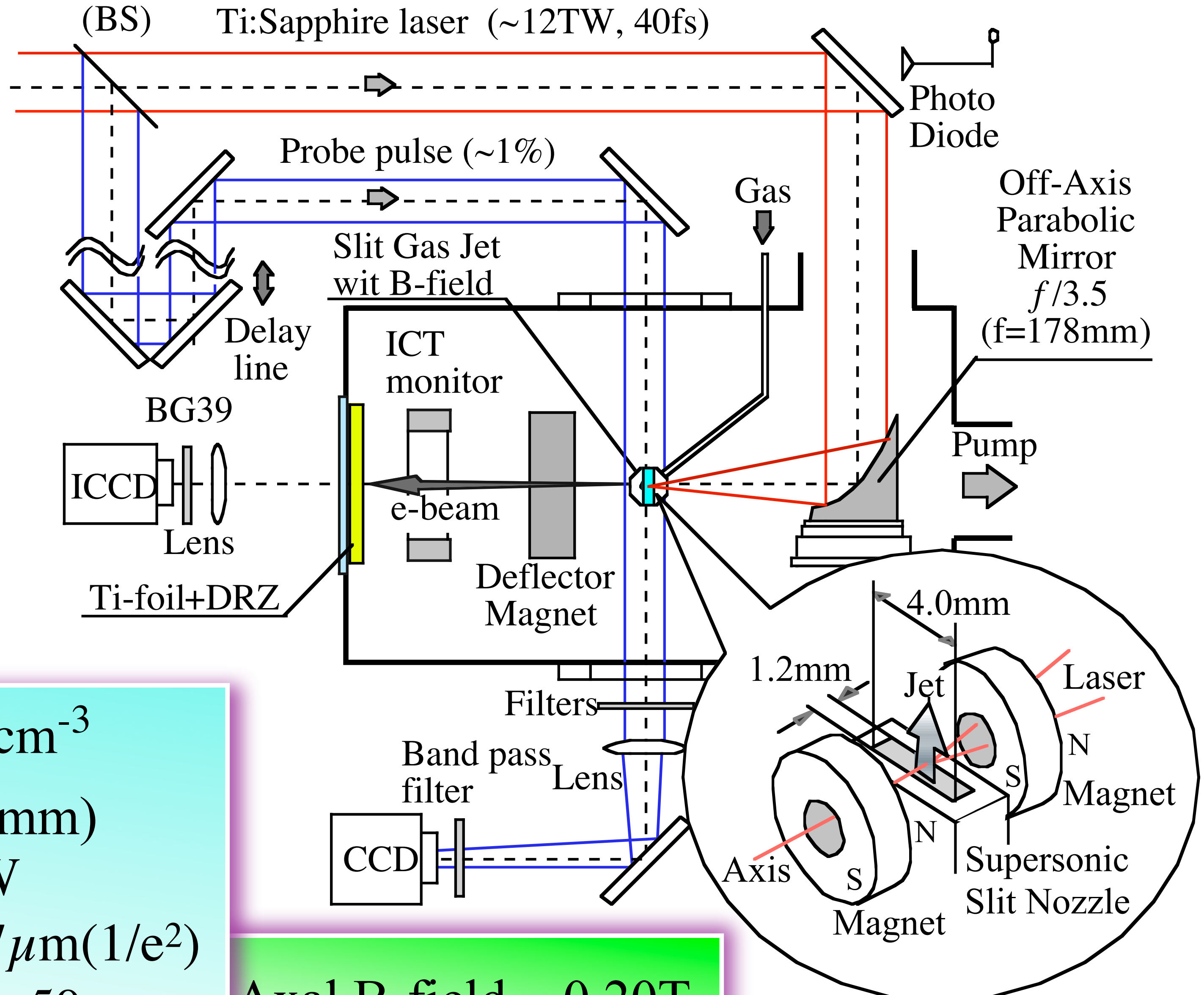






Repeatable LWFA with external B-field

T.Hosokai,et al.,Phys Rev.Lett. 97, 075004 (2006)



He Gas ~4×10^{19}cm^{-3}

$F^{\#}$=3.5 (f = 178mm)

Laser 6 ~ 12 TW

Focal spot ~ 5-7μm(1/e^2)

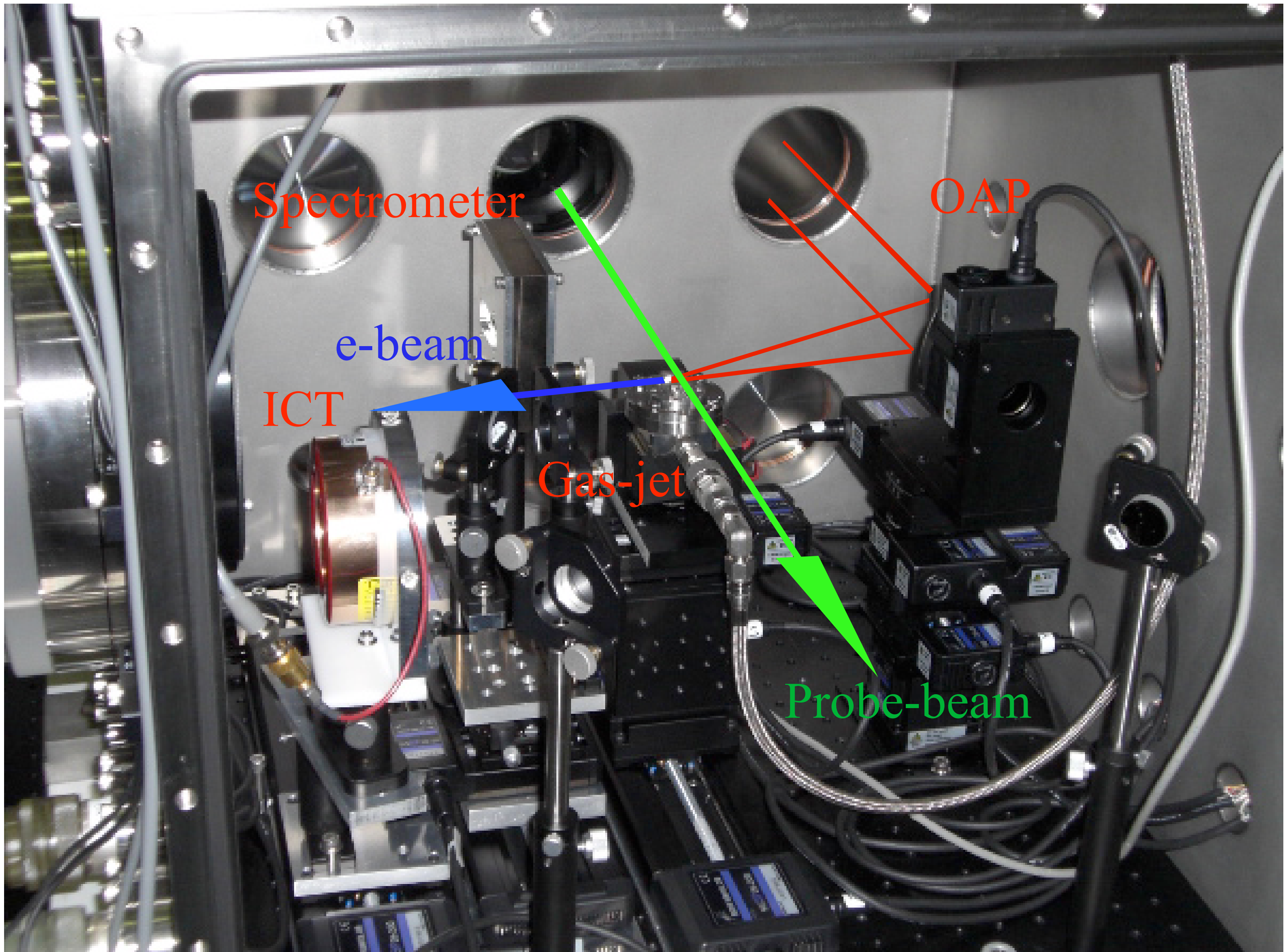
Rayleigh length ~50μm

Axal B-field ~ 0.20T

T.Hosokai Dept. of Energy Sciences, Tokyo inst. of Tech.

Repeatable LWFA with external B-field

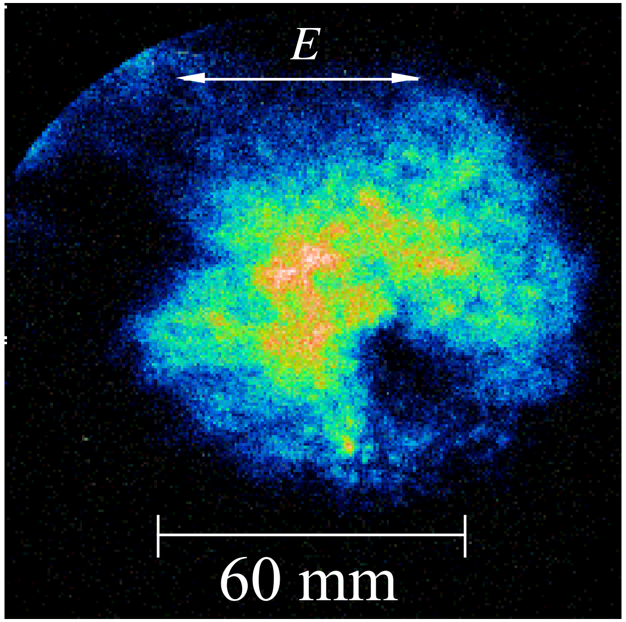
T.Hosokai,et al.,Phys Rev.Lett. 97, 075004 (2006)



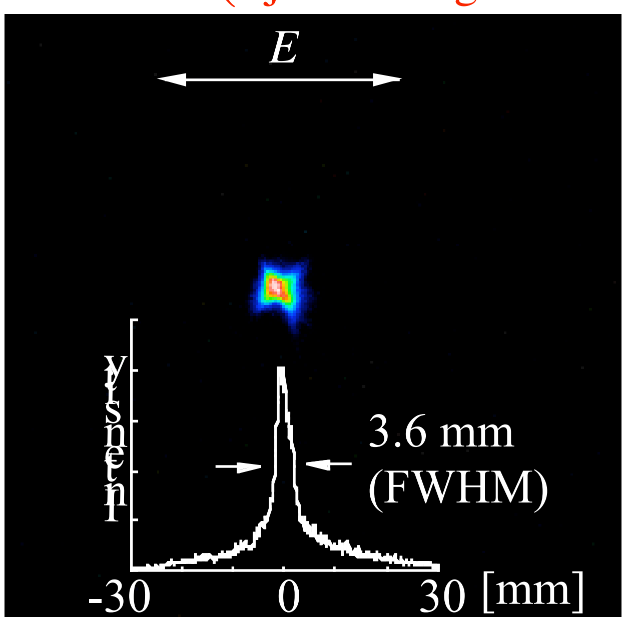
He Gas ~
$F^{\#}$=3.5 (
Laser 6 ~
Focal spo
Rayleigh

Repeatable e-Beam profiles (@ 300mm from focus point)

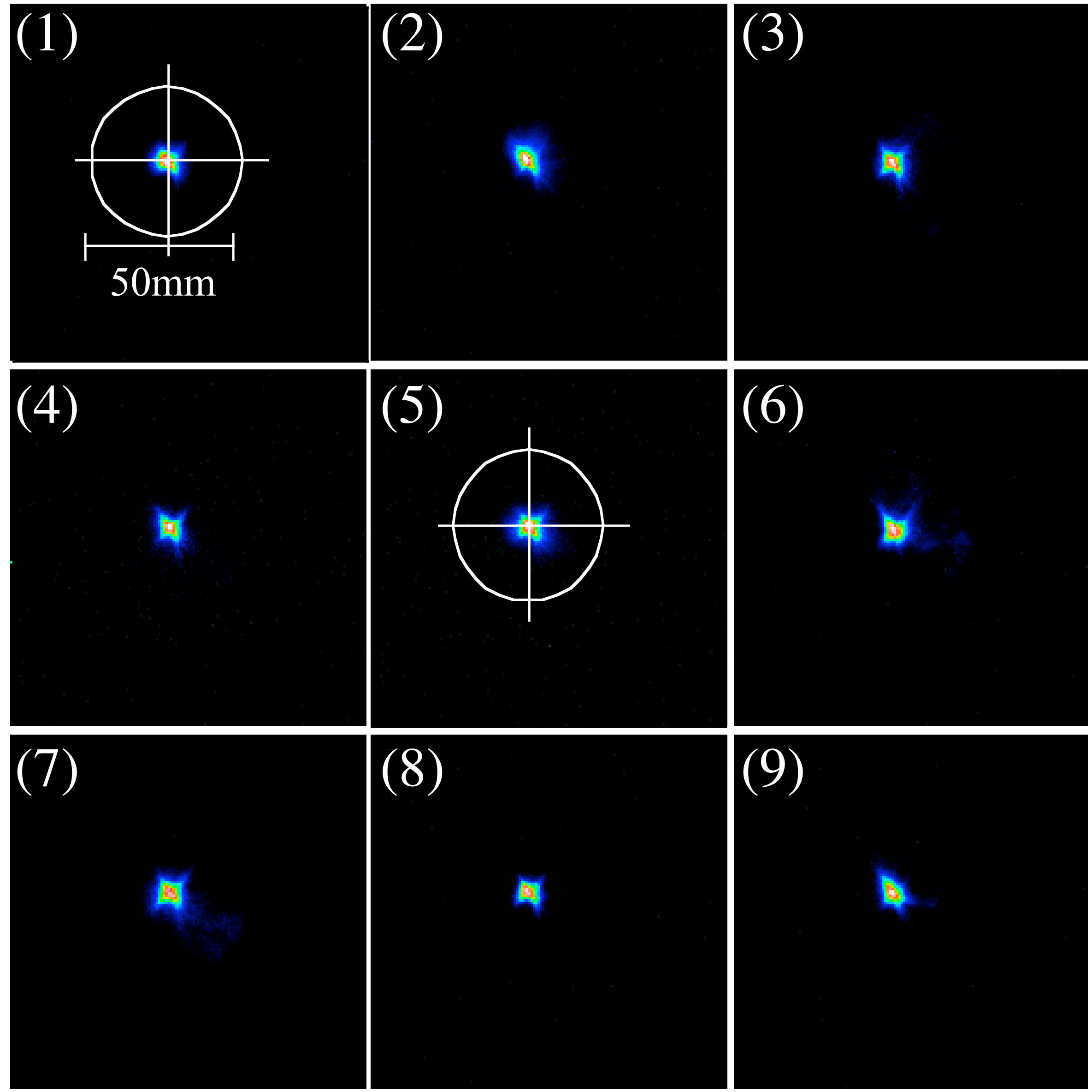
B＝ 0 (Ejection angle ~10°)



B＝ 0.2T (Ejection angle ~0.6°)



9 successive shots



(Transverse geometrical emittance ~0.02π mm mrad)

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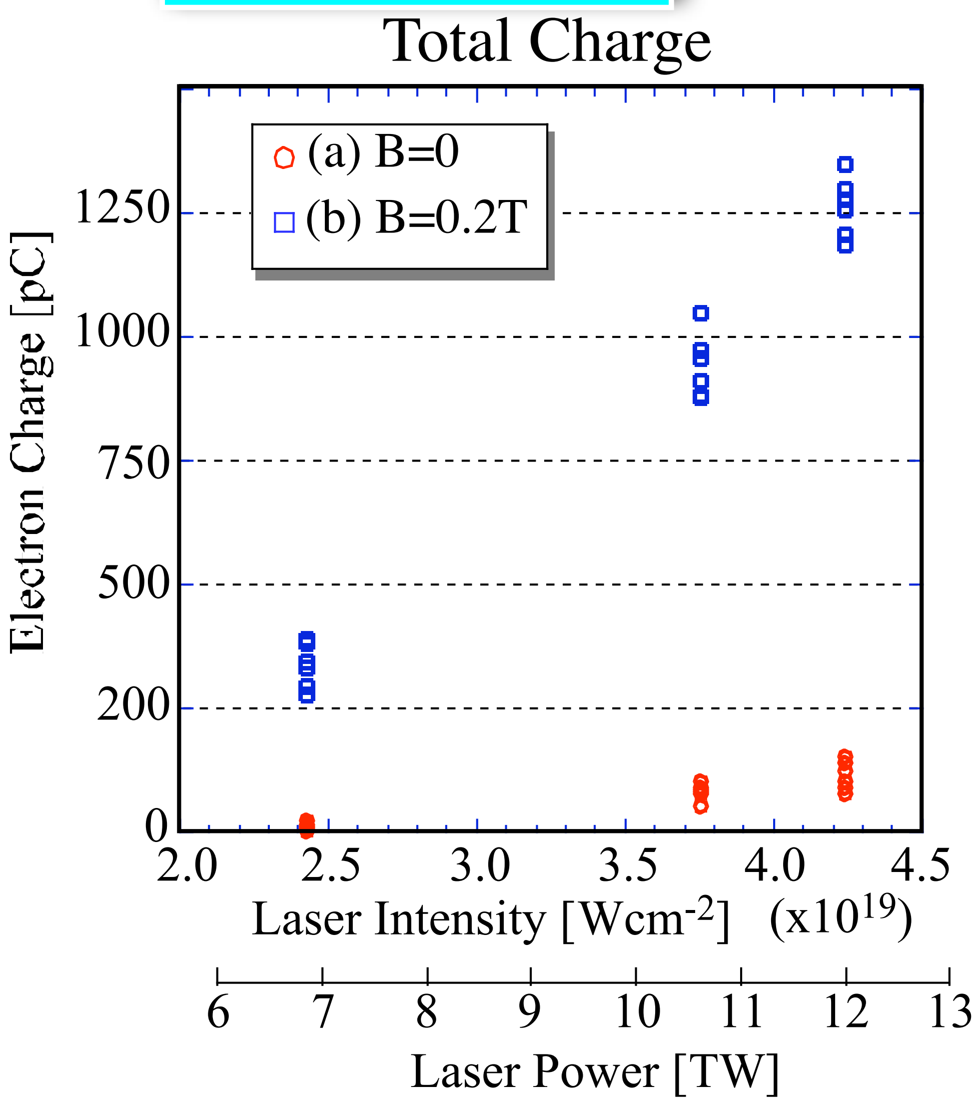
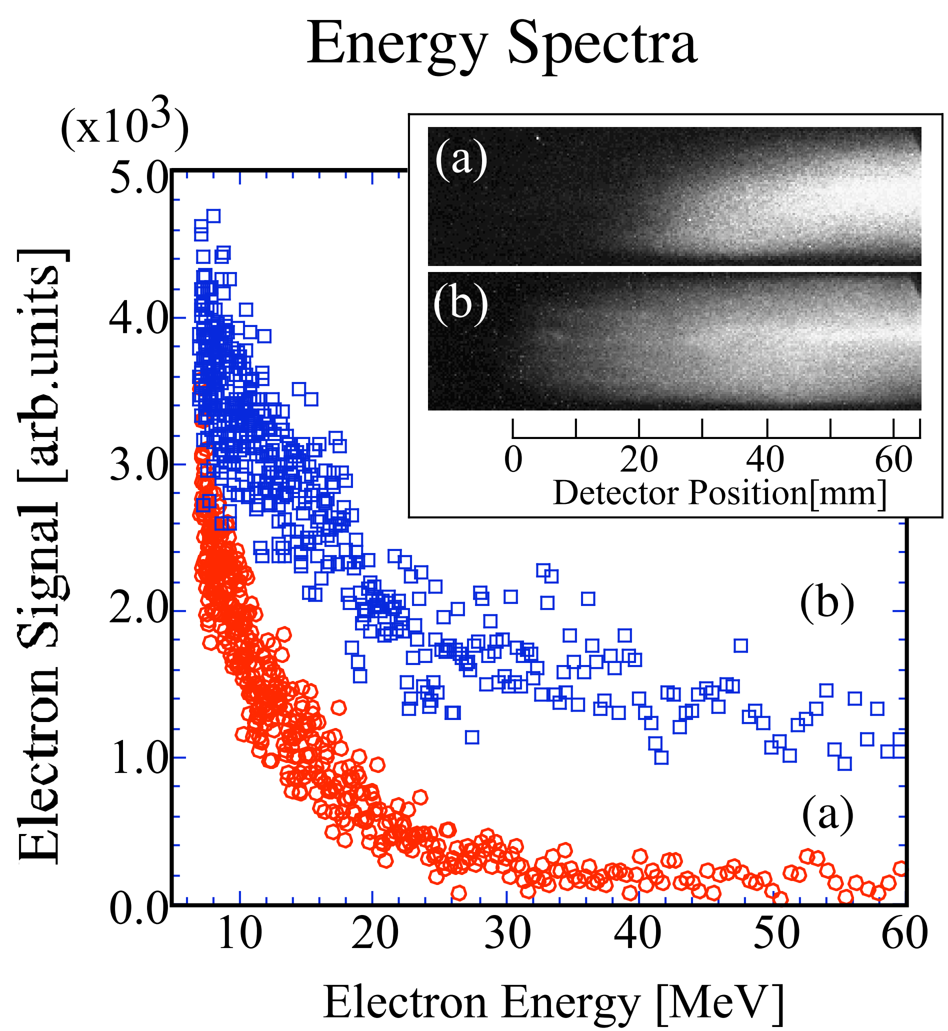
Enhanced e-Beam parameters

Beam size ~ x 1/20
Total charge ~ x10
Charge density ~ x 200





T_h~25MeV

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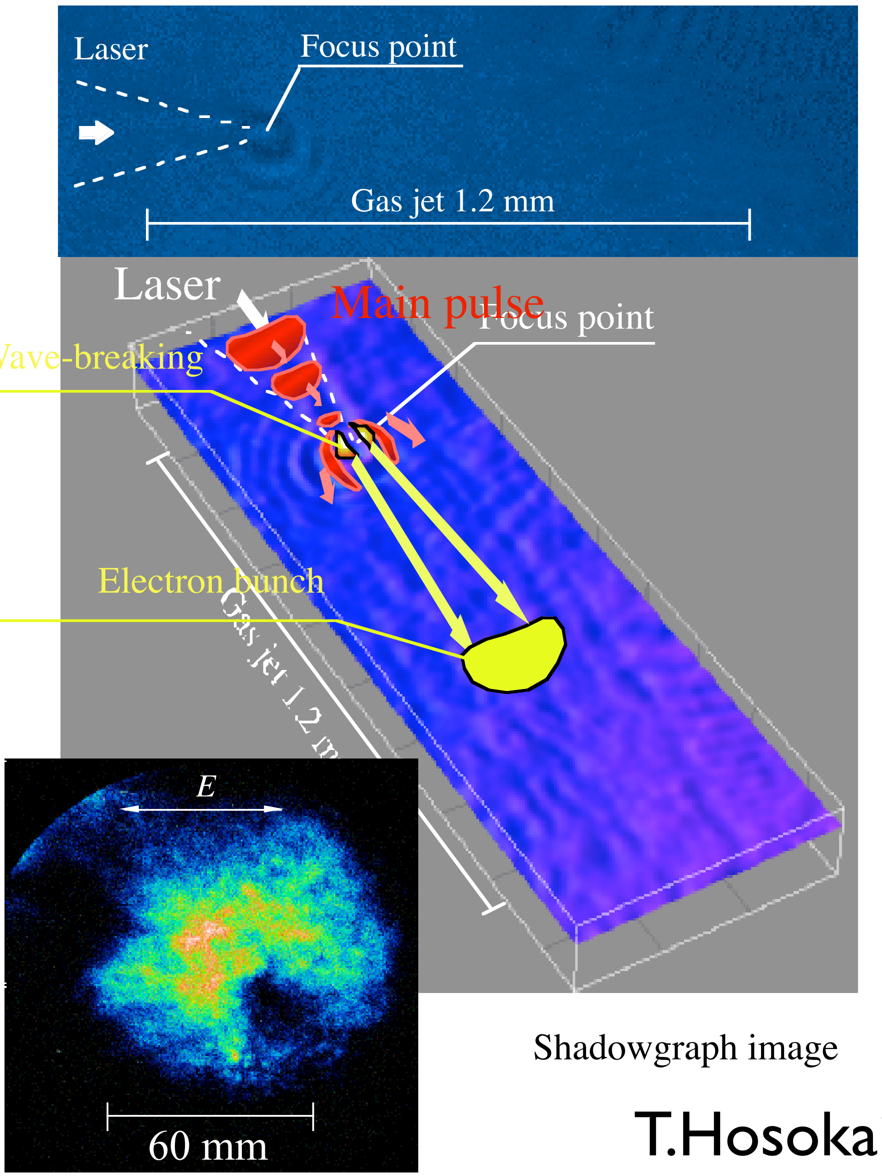
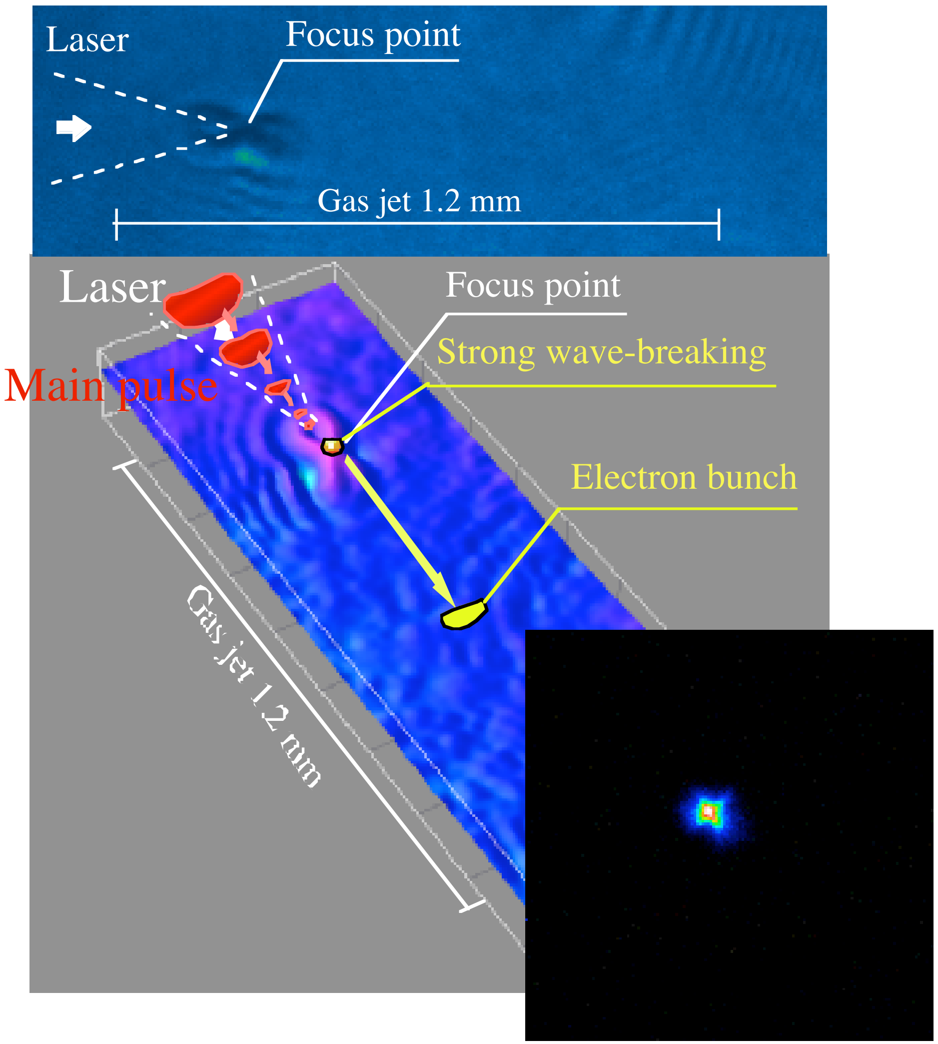
Formation of transient plasma micro-optics (TPMO)
TPMO suppress laser diffraction

T.Hosokai,et al.,Phys Rev.Lett. Submitted(Aug. 2008)

B=0 1.2ps before main pulse



B=0.2T



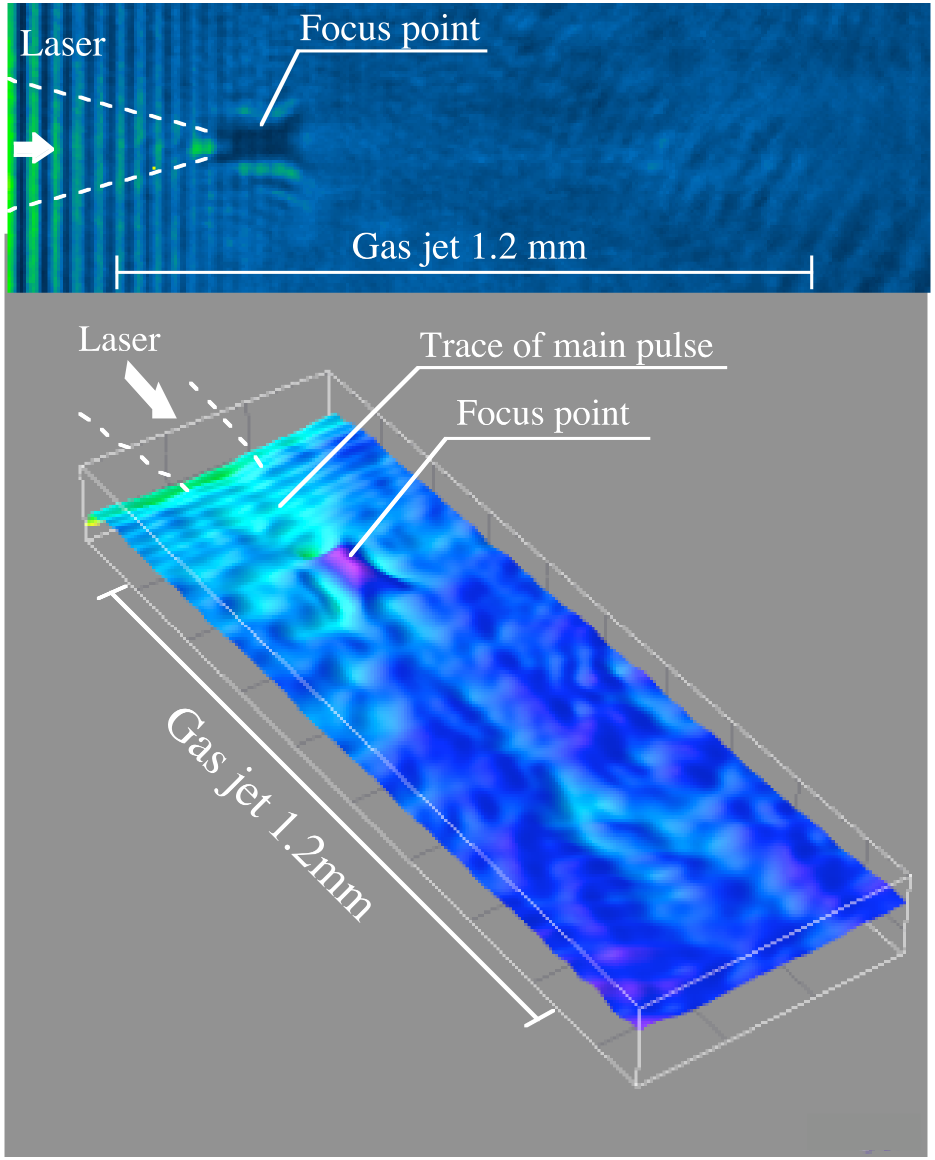
Shadowgraph image

T.Hosokai,et al.,Phys Rev.Lett. 97, 075004 (2006)

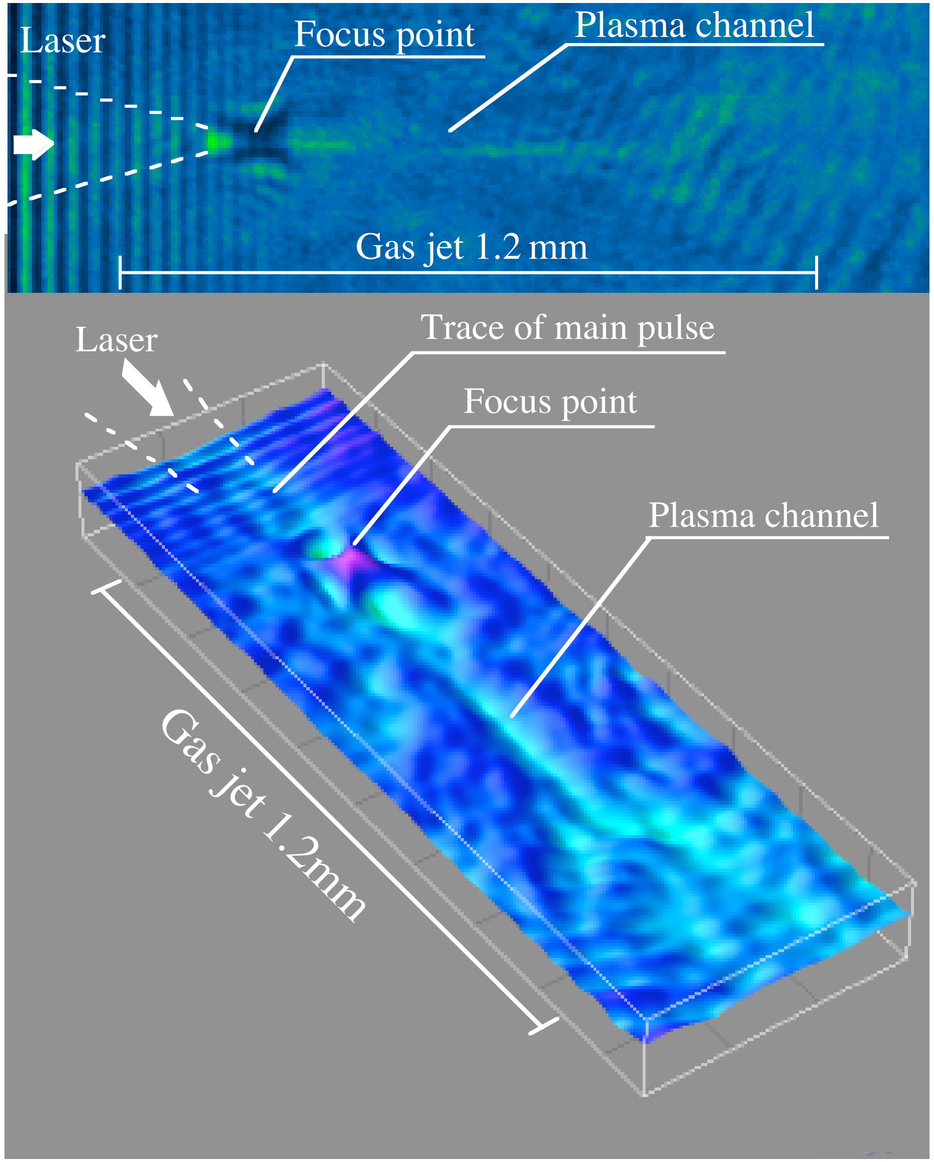
T.Hosokai Dept. of Energy Sciences, Tokyo inst. of Tech.

Stronger B-field experiment (1.2 mm gas-jet) with channel formation by ps pre-pulse tuning

Pre-pulse case (a), B=1T



Pre-pulse case (b), B=1T



1.2ps before main pulse

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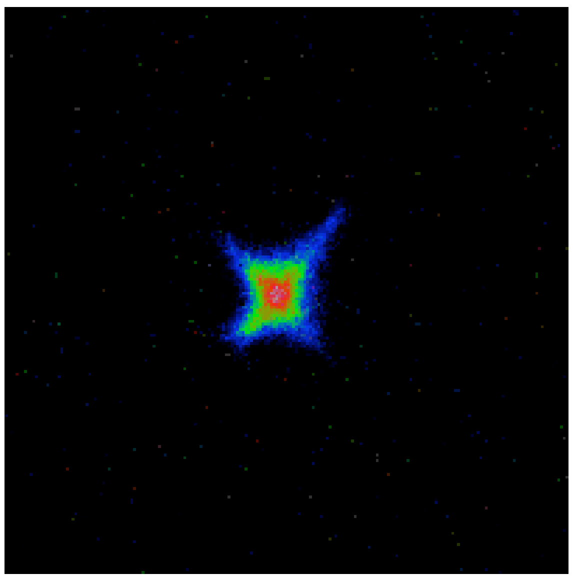
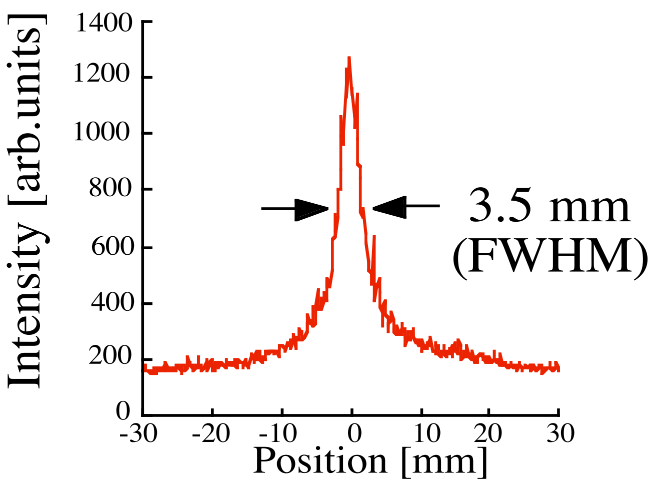
1.2 mm gas-jet experiment (e-Spot & energy spectra)
Demonstration of 2-staged acceleration

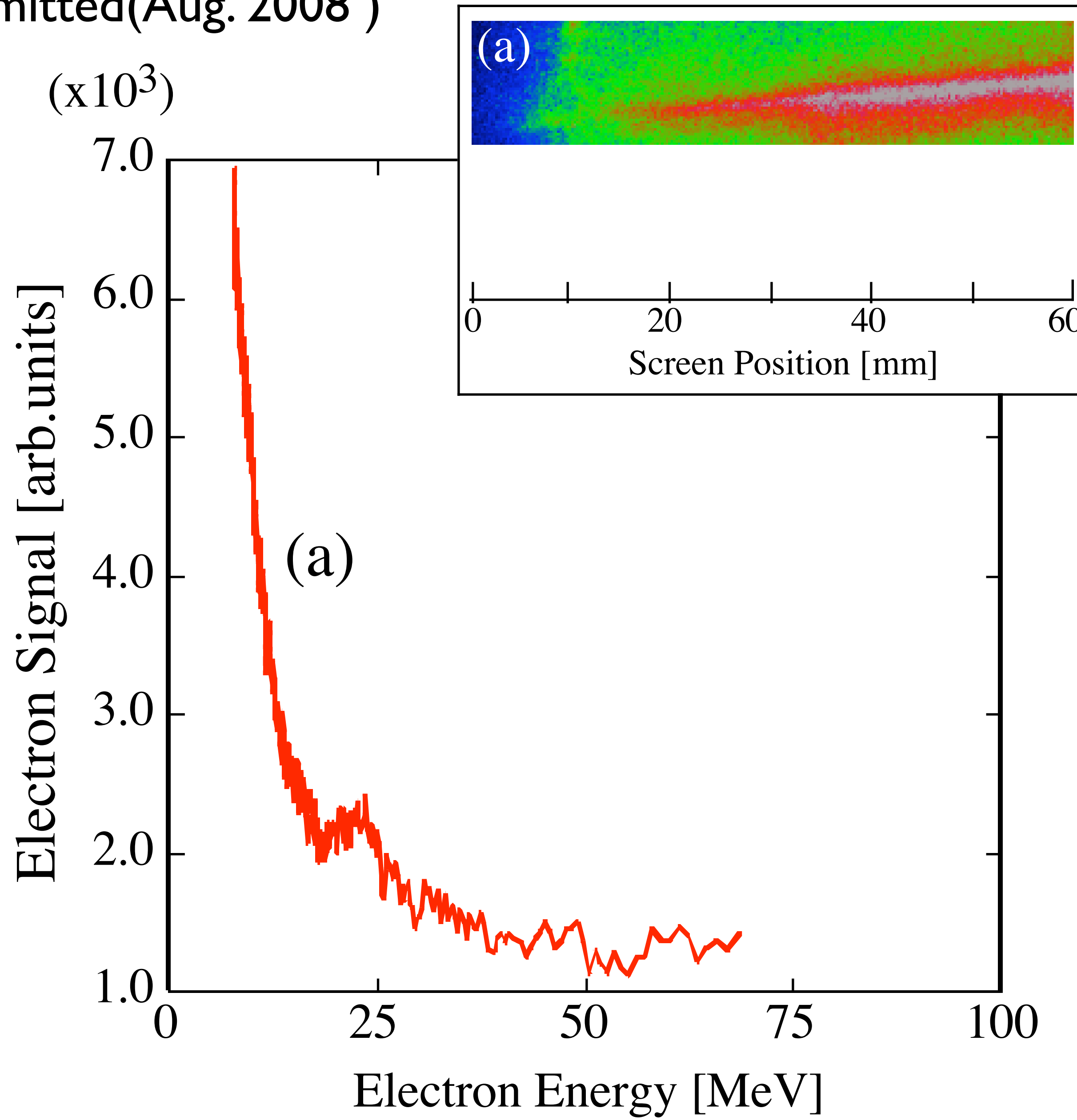
T.Hosokai,et al.,Phys Rev.Lett. Submitted(Aug. 2008)

Typical electron spot image

(300 mm from focal point)





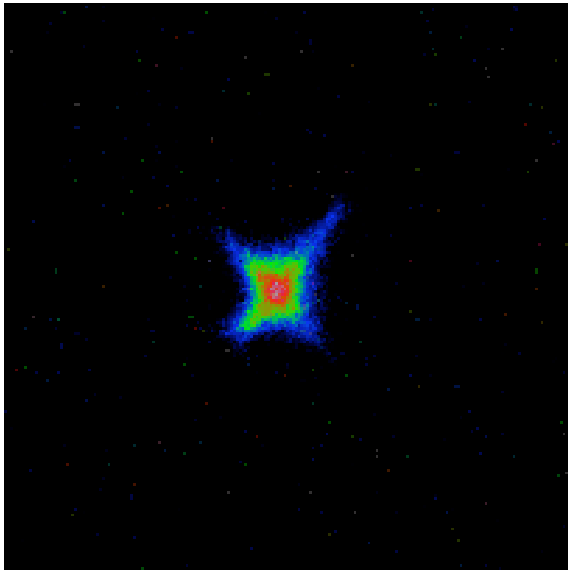


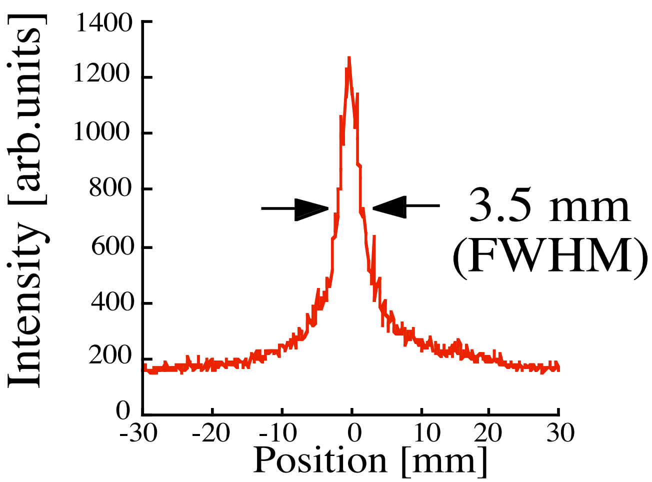
1.2 mm gas-jet experiment (e-Spot & energy spectra) Demonstration of 2-staged acceleration

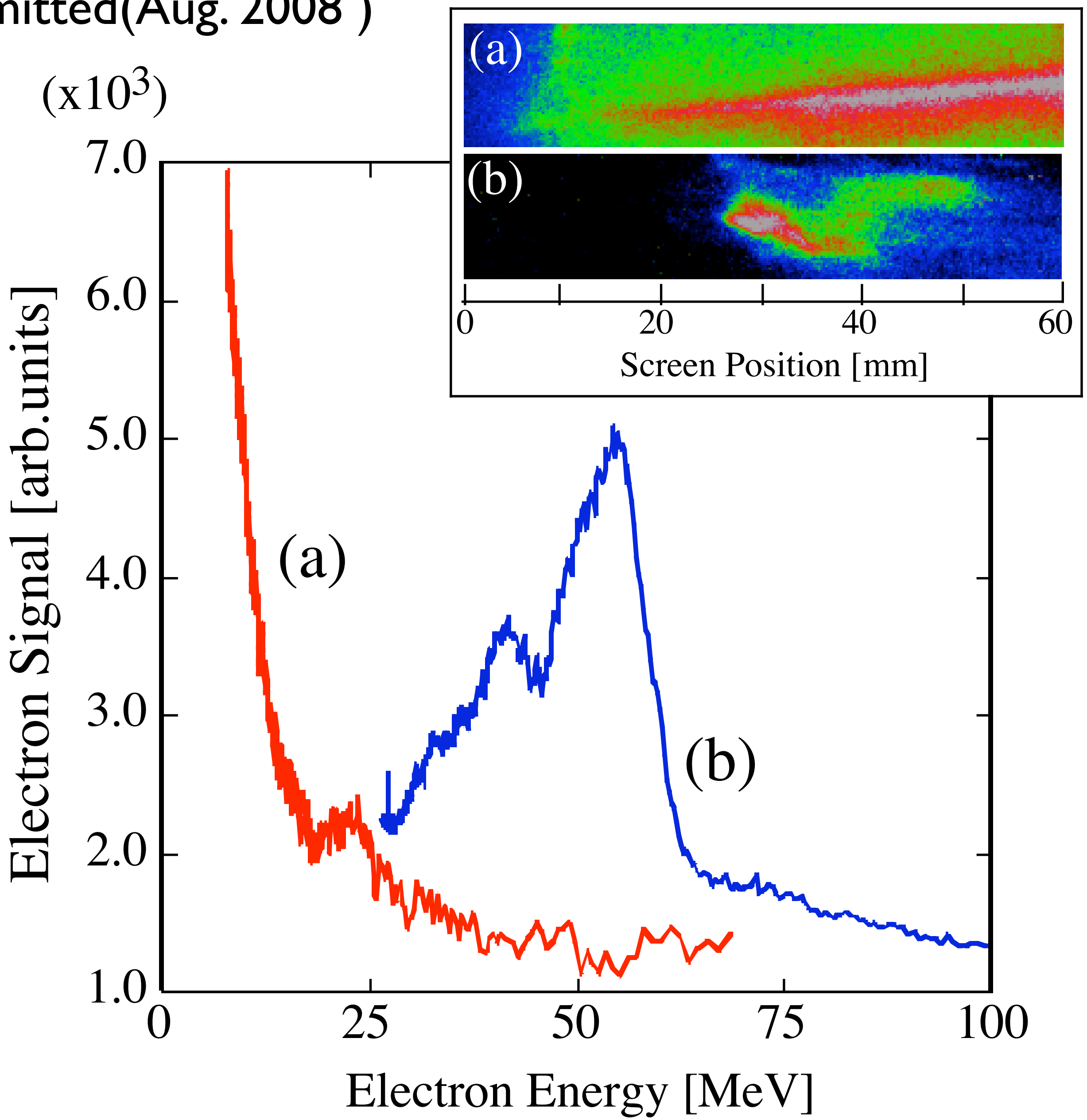
T.Hosokai,et al.,Phys Rev.Lett. Submitted(Aug. 2008)

Typical electron spot image

(300 mm from focal point)







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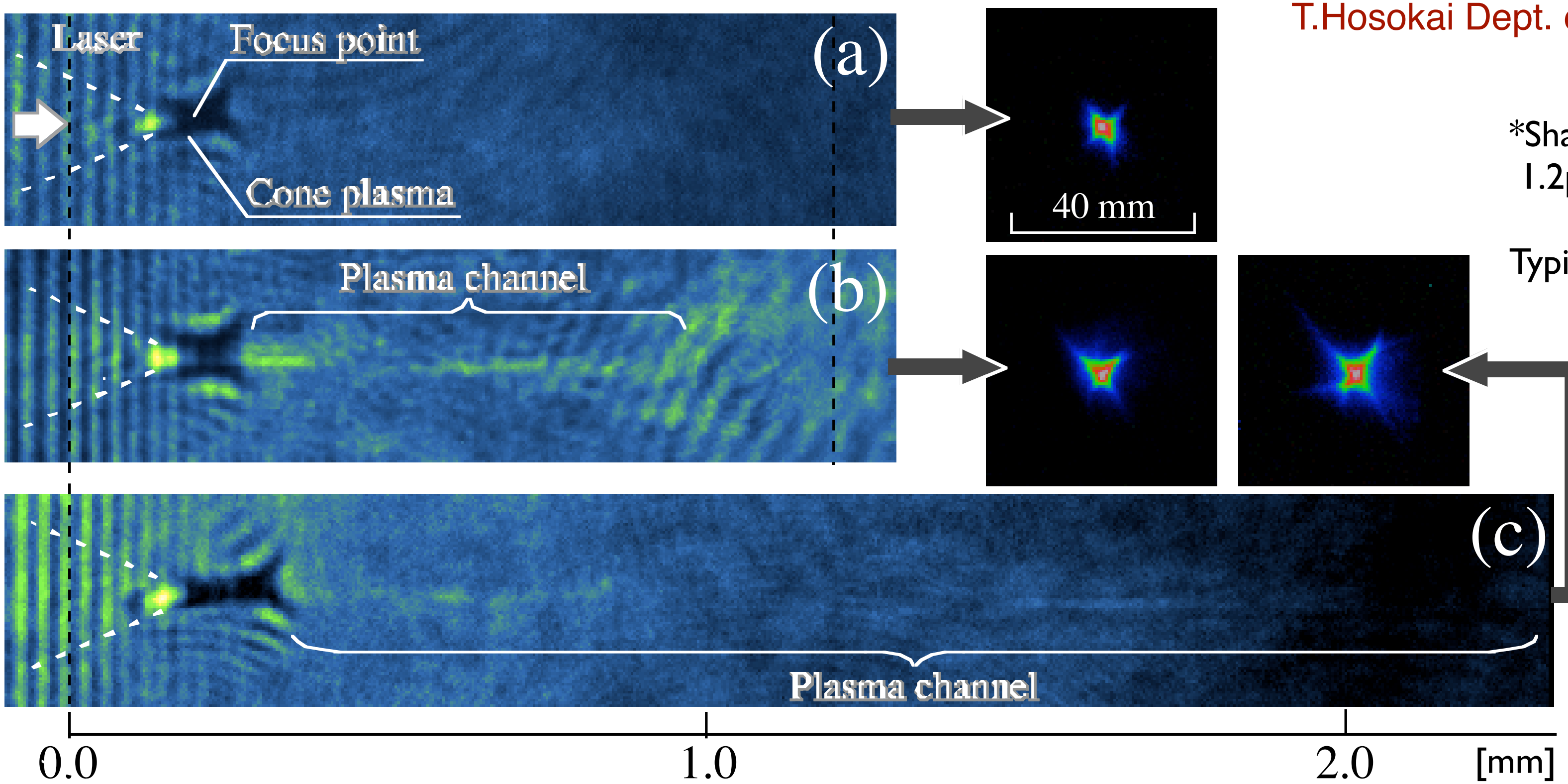
4.0 mm gas-jet experiment (e-Spot & energy spectra)
Demonstration of 2-staged acceleration

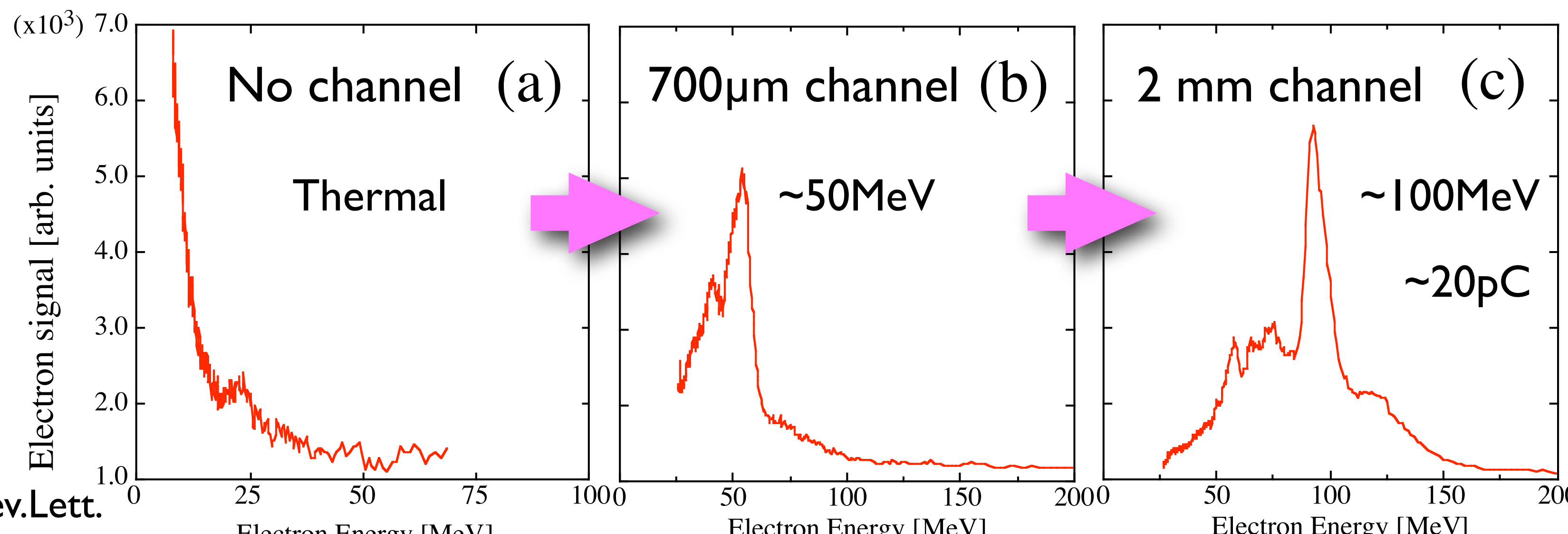
T.Hosokai Dept. of Energy Sciences,
Tokyo inst. of Tech.



*Shadowgraph:
1.2ps before main pulse

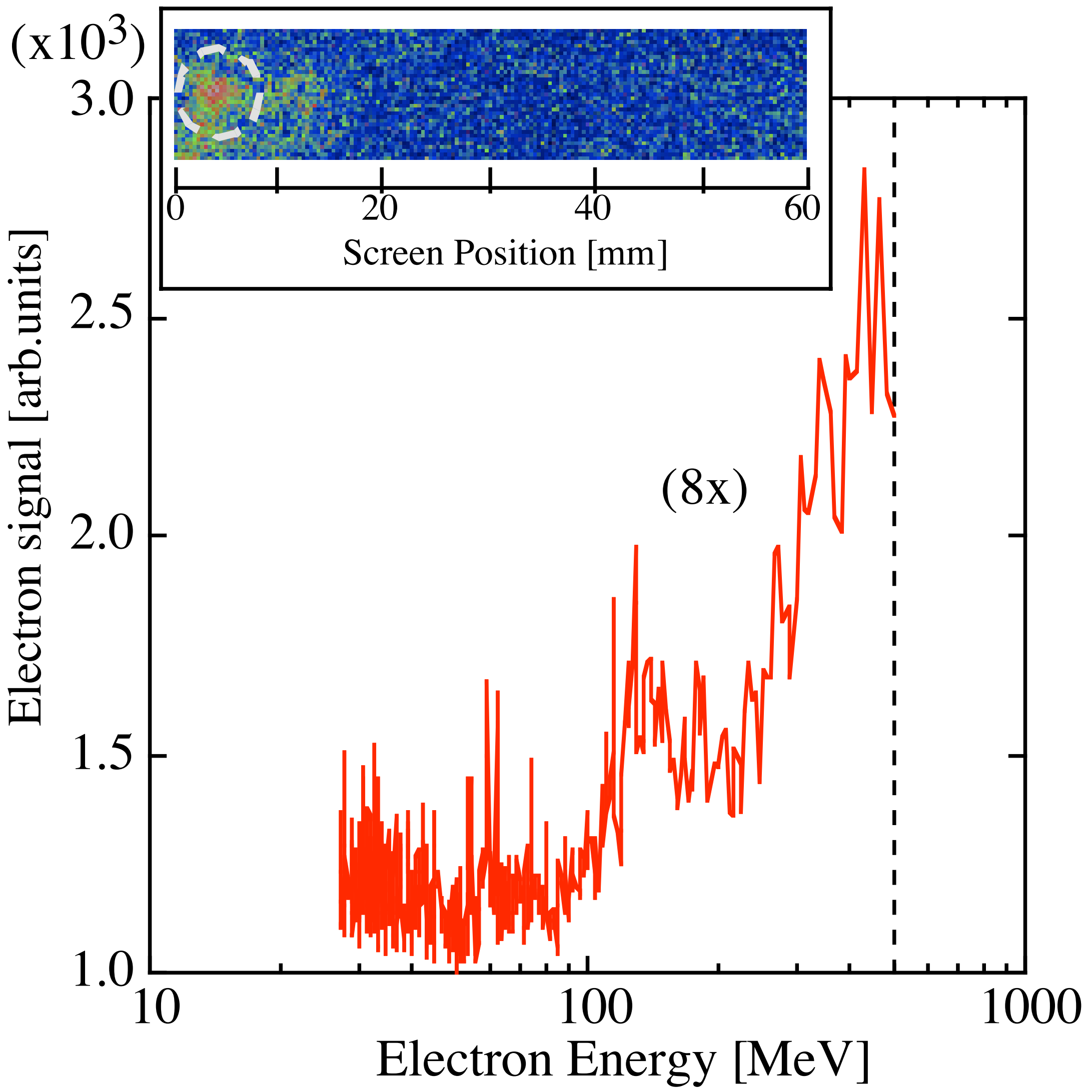
Typical e-beam profile

Evolution of energy spectrum (Staged Acc.)



T.Hosokai,et al.,Phys Rev.Lett. Submitted(Aug. 2008)

Highest energy electrons measured



Single-shot measurement

Peak energy ~0.45GeV

(Detection limit)

~1pC/shot

0.02πm mmrad

Drive laser only ~7TW

Prepulse (b)

4.0 mm nozzle (He)

Gas density~4×10^{19}cm^{-3}

T.Hosokai,et al.,Phys Rev.Lett.
Submitted(Aug. 2008)

Summary

- Table-top MeV-class Compton x-ray source can be possible by using the LWFA.
- Present problems of the LWFA is the stability of the output beam.
- Electron injection as well as capillary formation in the B-field are effective.