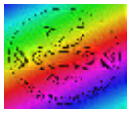

Nuclear Engineering Research Laboratory
Graduate School of Engineering
University of Tokyo

Mono-energetic Electron Generation and Plasma Diagnosis Experiments in a Laser Plasma Cathode

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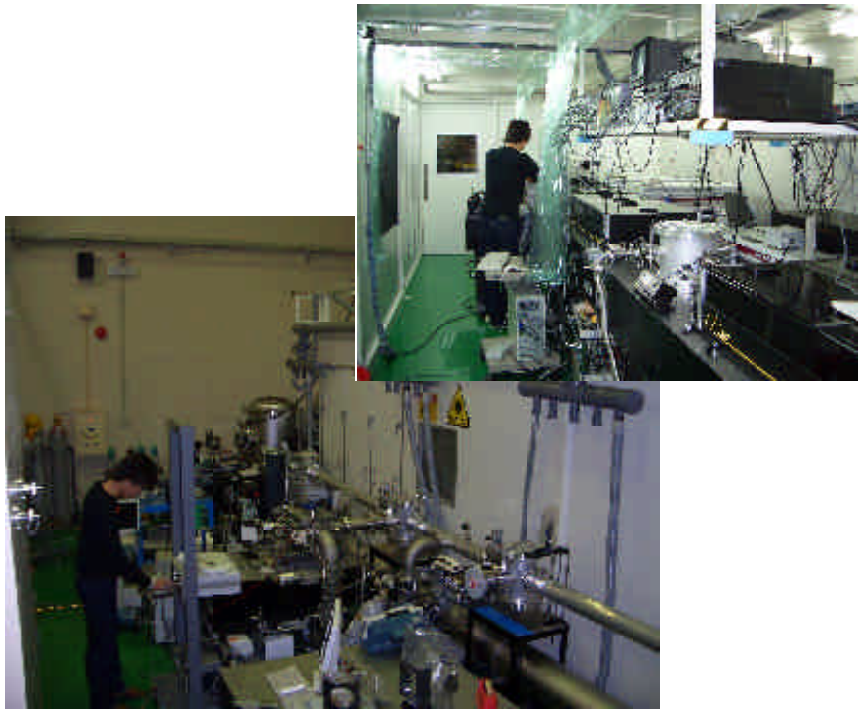
[1]·National Institute of Radiological Sciences JAPAN

A. Yamazaki[2], H. Kotaki[2], M. Kando[2], K. Nakajima[2] and S. V. Bulanov[2]

[2]·Advanced Photon Research Center, Japan Atomic Energy Research Institute Kansai

The physics and Applications of High Brightness Electron Beams, Erice (Italy), 10th-14th Oct. 2005.

University of TOKYO Nuclear Professional School
Laser Acceleration Group



17TW-37fs Ti:Sappire Laser facility

Supervisor Prof. **Mitsuru UESAKA**
Staff (Experiment) **Tomonao HOSOKAI**
Staff (Experiment) **Kenichi KINOSHITA**
Staff (Simulation) **Alexei ZHIDKOV**
D3-student (Simulation) **Takeru OHKUBO**
D3-student (Experiment) **Atsushi YAMAZAKI** (Kyoto Univ)
M1-student (Experiment) **Akira MAEKAWA**
M1-student (Experiment) **Kazuyuki KOBAYASHI**

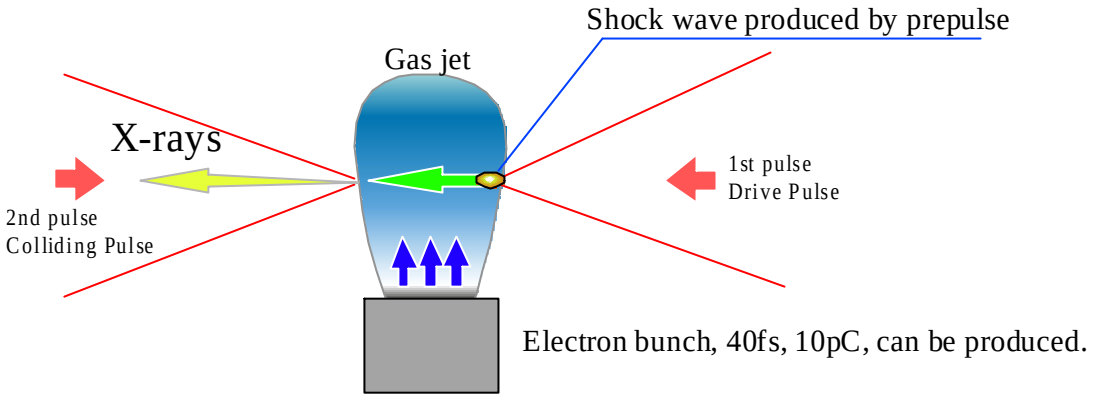
(Collaborators)

JAERI-APRC **Masaki KANDO**
JAERI-APRC **Hideyuki KOTAKI**
JAERI-APRC **Sergei V. BULANOV**
JAERI-APRC **Kazuhisa NAKAJIMA**
KEK

Research Goals -- Femtosecond Electron Beam

High quality femtosecond electron beam

- 10 fs pulse duration
- 1 nC charge
- $\Delta E/E \sim 1\ \%$
- Jitter free



⬇

Femtosecond pump-probe analysis

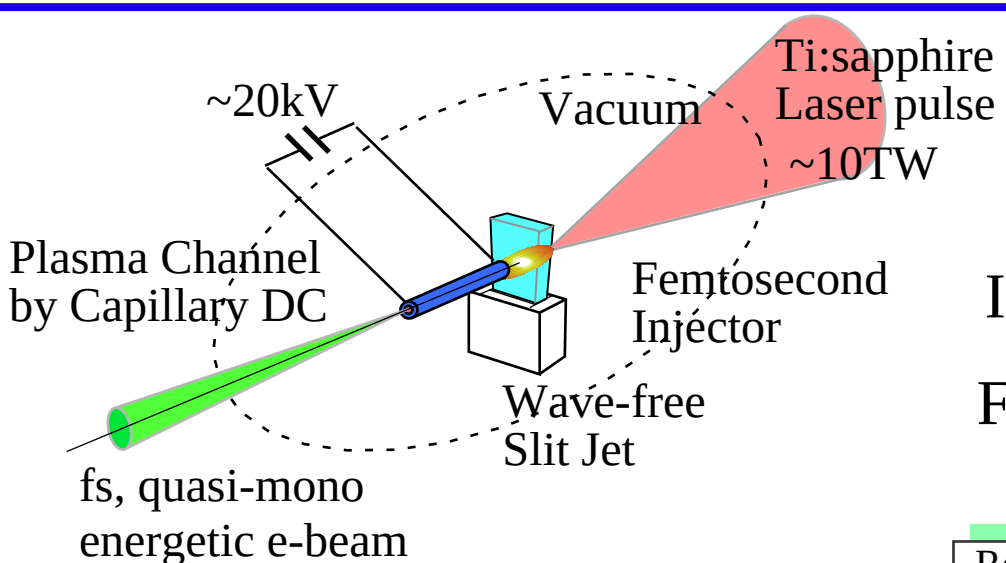
Fast processes in radiation chemistry

Electronic behavior in THz devices

Femtosecond X-ray generation through laser Compton scattering

E ~ 1 - 10 keV, (~ 10^9 photon/s, within 1 deg)

2-staged Acceleration



	Low density ($\sim 10^{17} cm^{-3}$)	High density ($\sim 10^{19\text{-}20} cm^{-3}$)
Dephaseing Length	~10cm	~100μm
Charge	few ~pC	huge ~nC
Acc. Energy	High	Low
Plasma wavelength	~100fs	~10fs
Wake-fields	Regular	few cycles
Optical guiding	Effective	???

2staged Acc.

Injector : Plasma Cathode

Further acc : Capillary DC

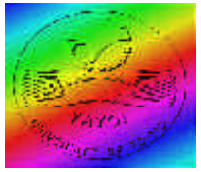
Requirements

- High Charge
- Uitrashort
- High Energy

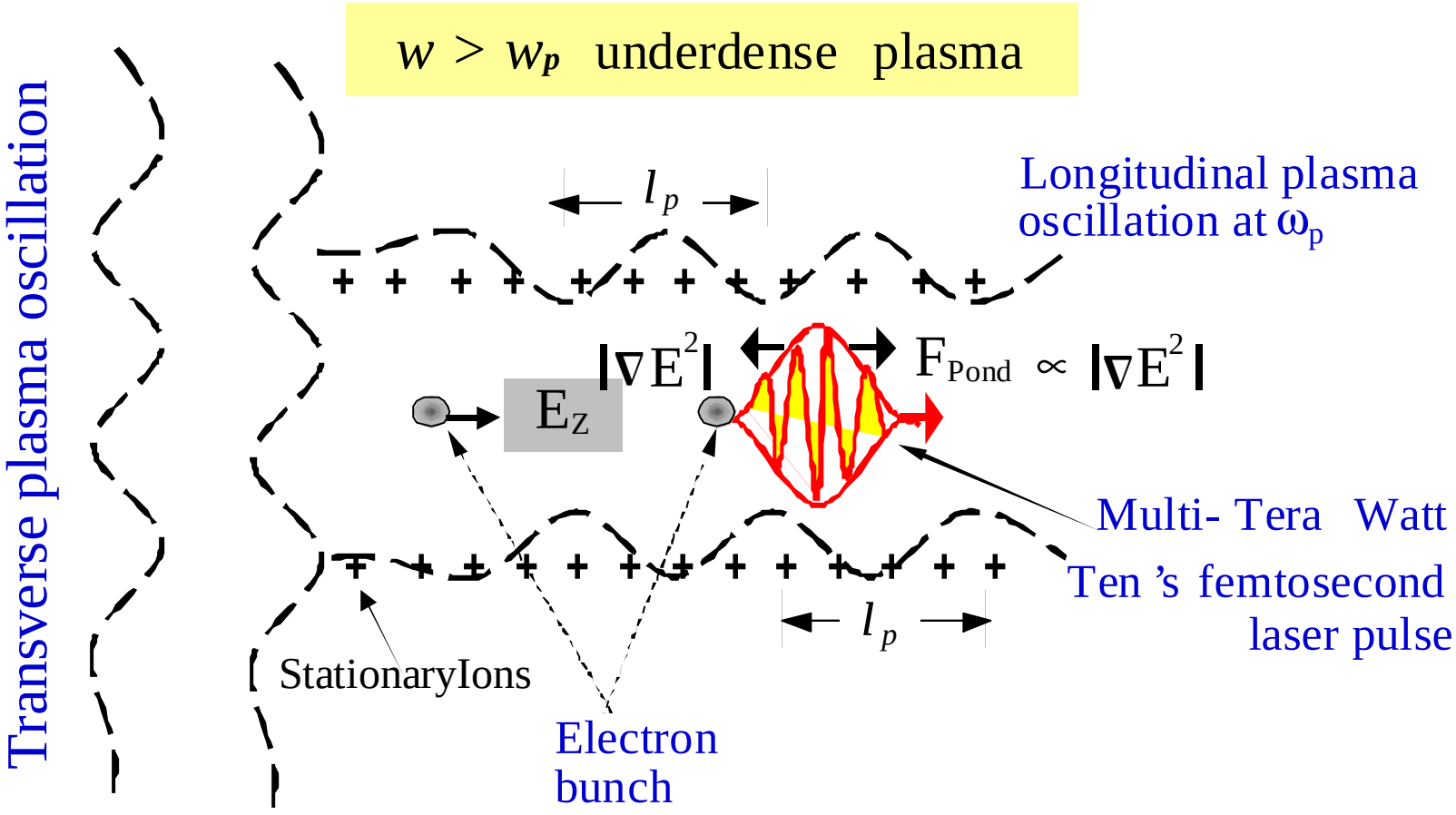
How to overcome the contradictory?

- High density gas jet for injector
- Low density with optical guiding for further acc.

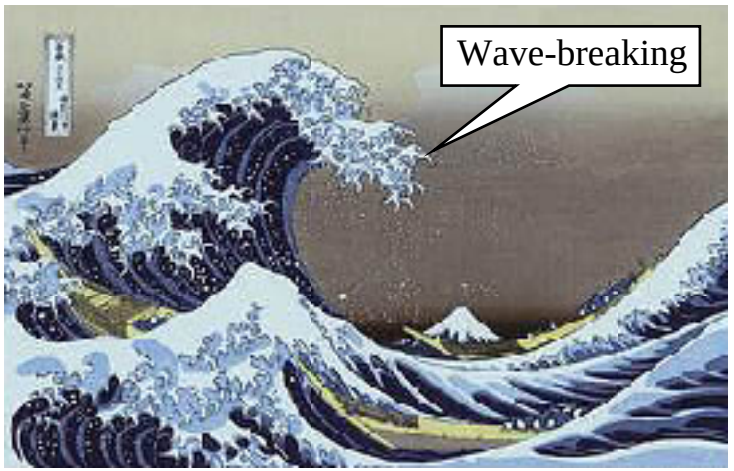
Laser Wakefield Accelerator



(Tajima and Dawson Phys. Rev. Lett. 43, 267, (1979))



Femtosecond Electron Injector by Plasma Wave Breaking



Rapid injection into correct acceleration phase → Femtosecond e- bunch

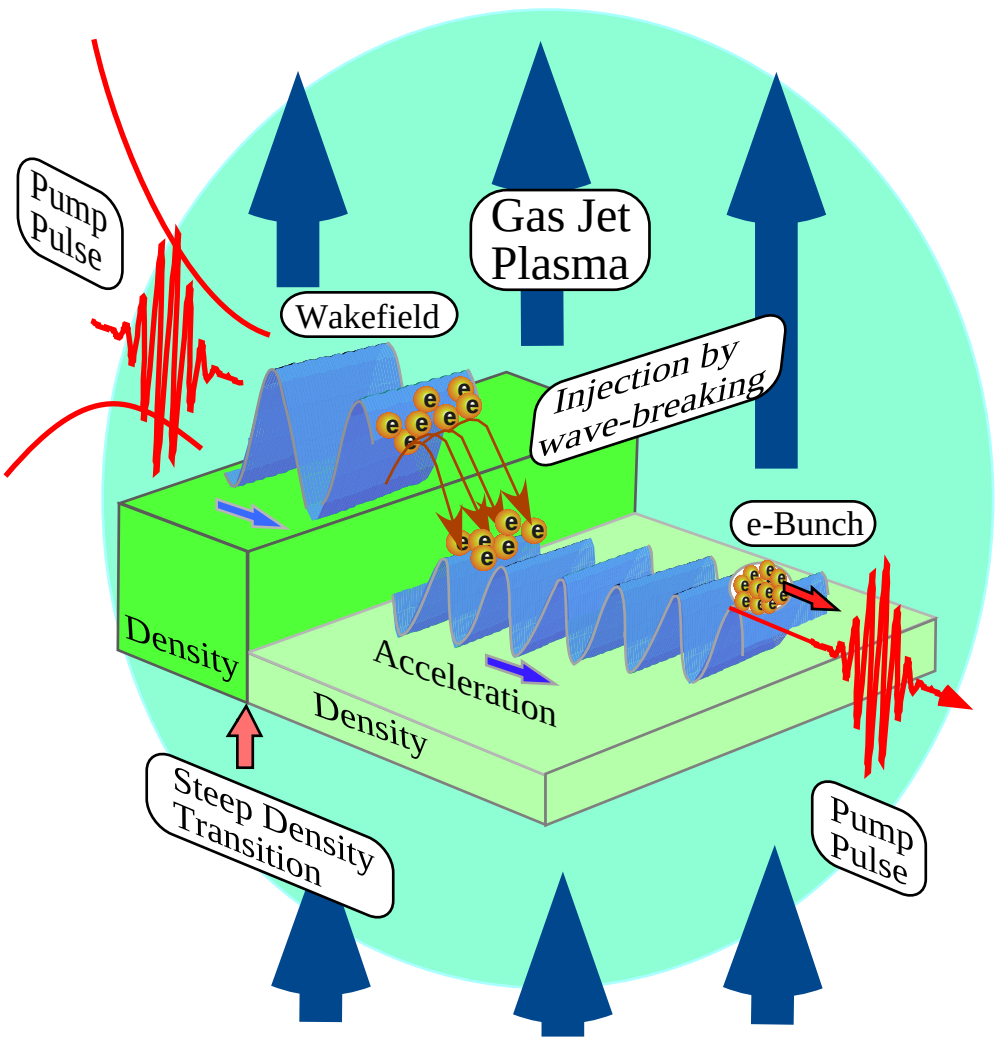
- Wave-breaking field

$E_B \sim [2(\omega/\omega_{pl}-1)]^{1/2}\, mc\omega_{pl}/e$

- Density gradient

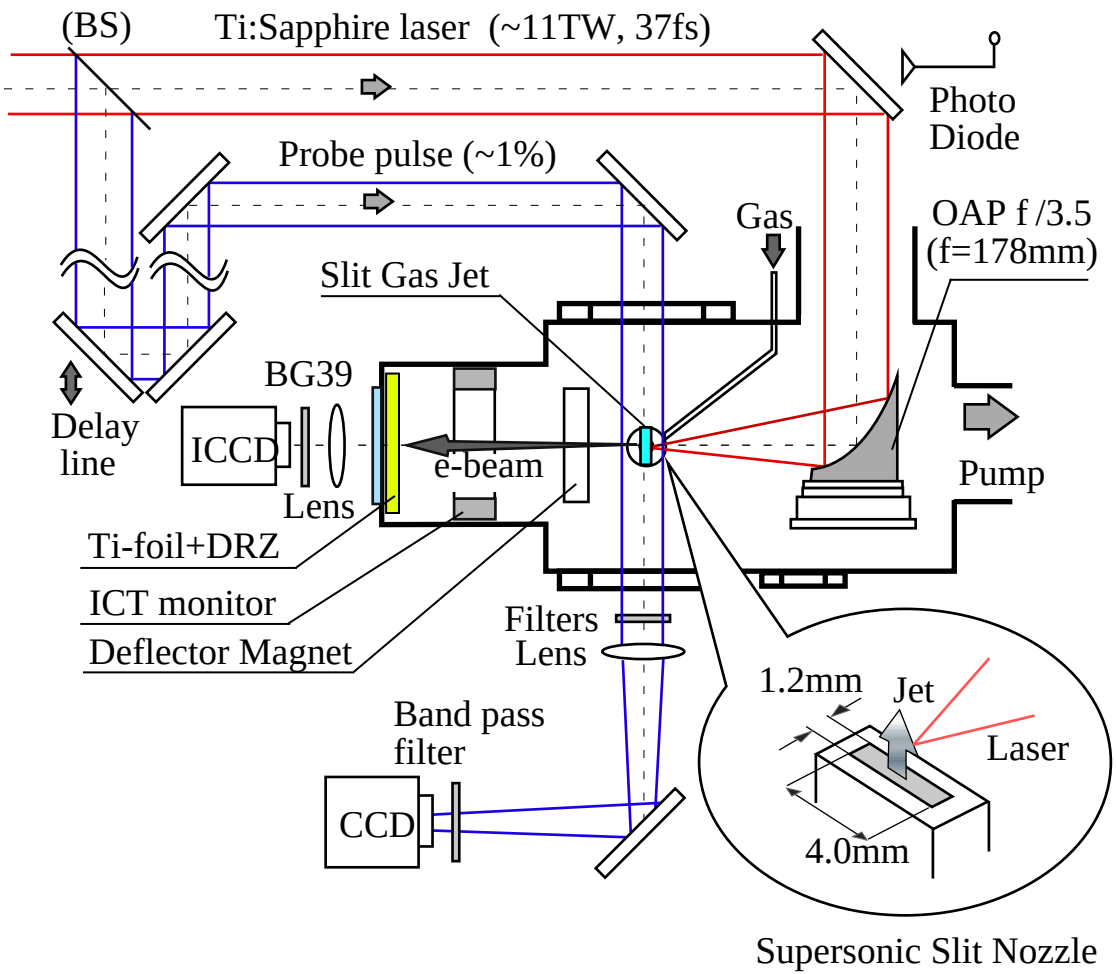
$\lambda_{pl}\, N/(dN/dx) \sim 1$

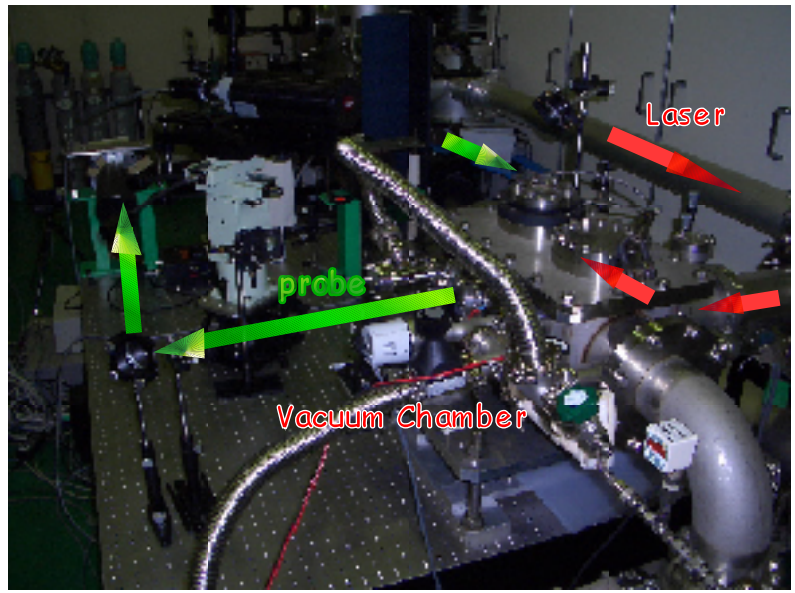
ω : Laser frequency
ω_{pl} : plasma frequency
$\lambda_{pl} = 2\pi c/\omega_{pl}$
λ_{pl}: plasma wavelength

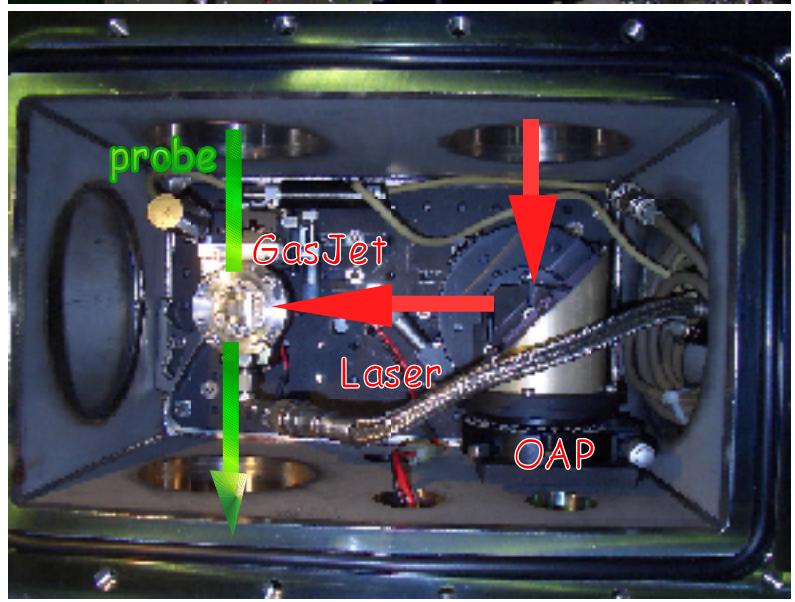


Reference : S.V.Bulanov, et al, Phys.Rev.E. 58, R5257

Experimental Setup at Univ. of Tokyo

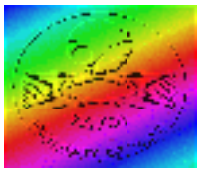




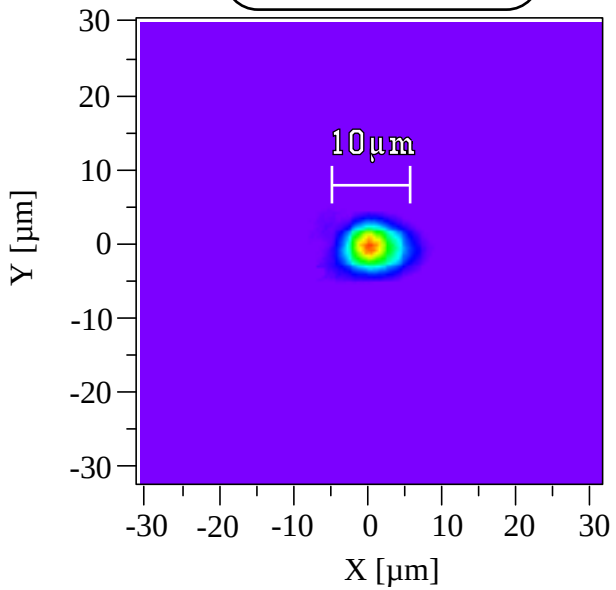


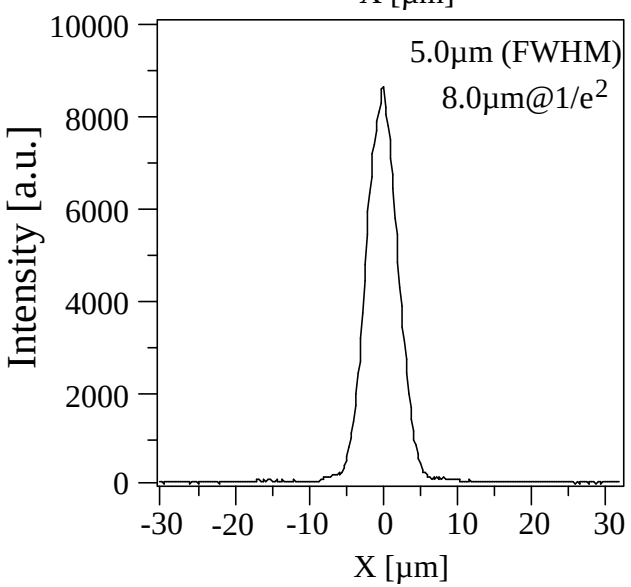
Gas density up to $6 \times 10^{19} cm^{-3}$ @80atm

Laser Parameters (Ti:Sapphire 17TW, 37fs)

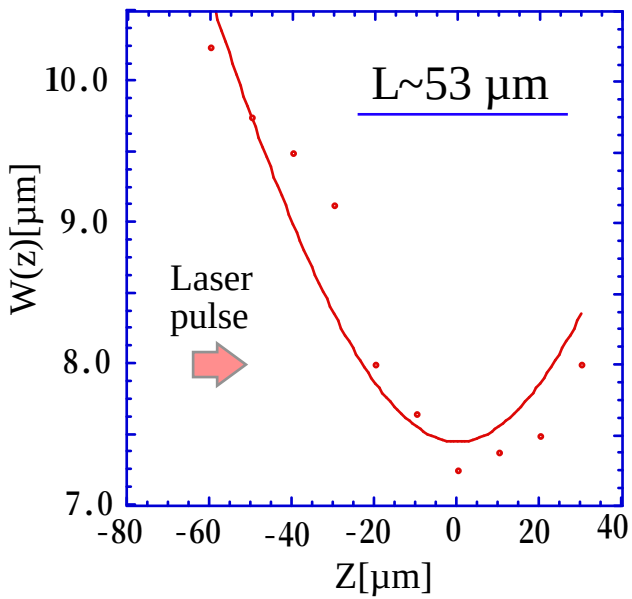


Laser spot

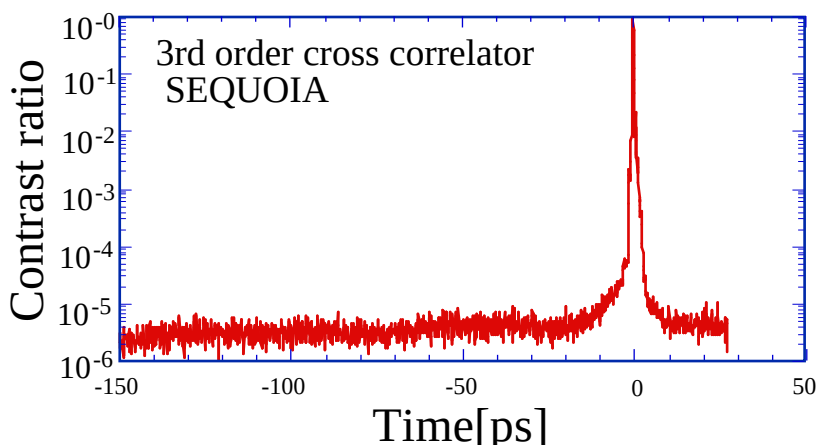




Rayleigh Length



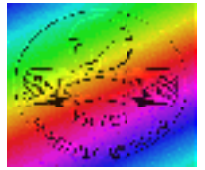
Contrast Ratio



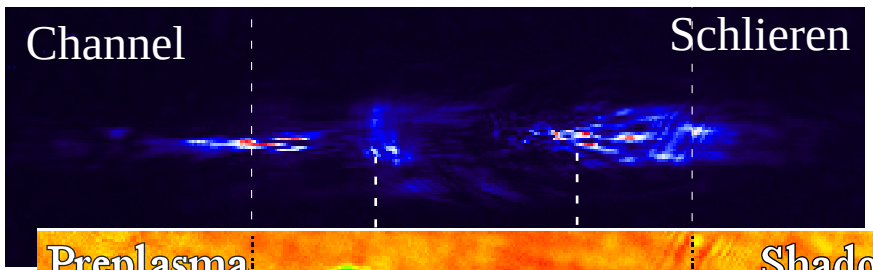
Focusing Parameters

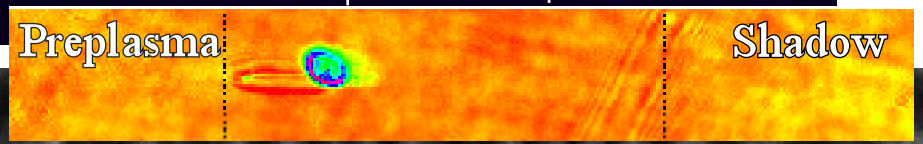
- OAP f =177mm
- Beam size D~50mm
- $F^{\#}$~3.5
- Spot size ~8.0 µm @1/e^2
- Rayleigh length ~53 µm
- Power Density for Main Pulse (~11TW)
  ~2.2x10^{19}Wcm^{-2}
  a_0~3.1
- Contrast Ratio 1:5x10^{-7}
- Power Density for Pre-pulse
  2ns~1.0x10^{13}Wcm^{-2}
  few ps~1.0x10^{16}Wcm^{-2}

Experimental Setup (Gas, Focusing, Beam Generation)

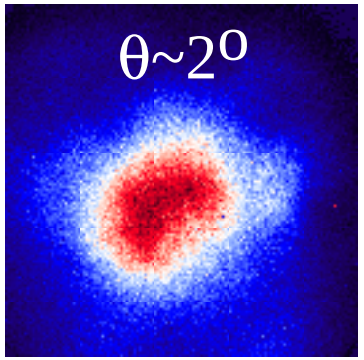


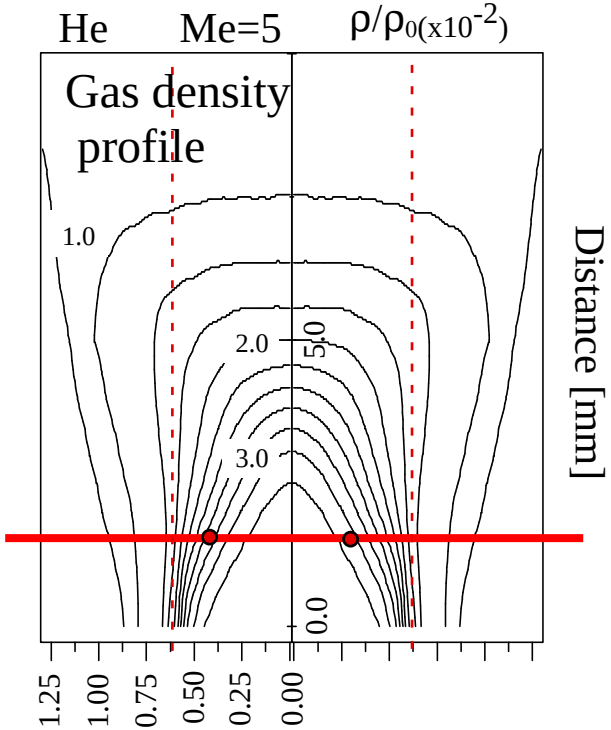
~11TW, 37fs Laser



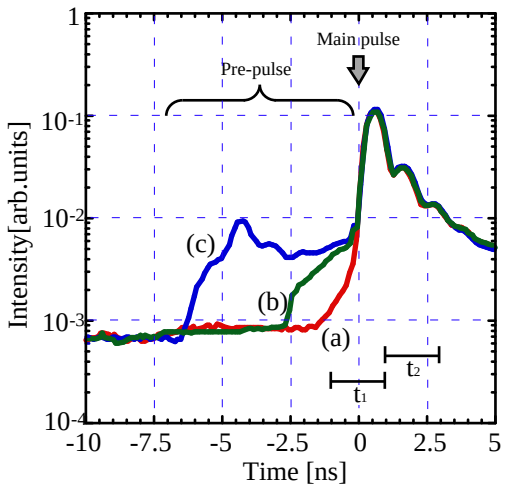


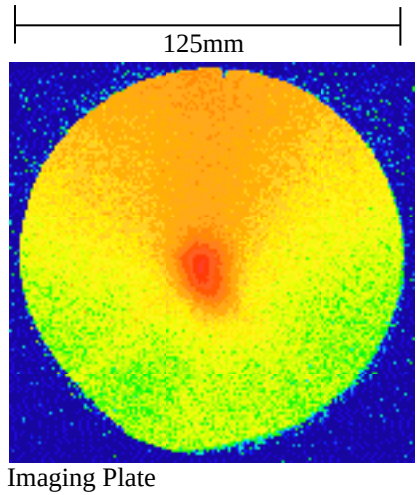
MeV electron bunch

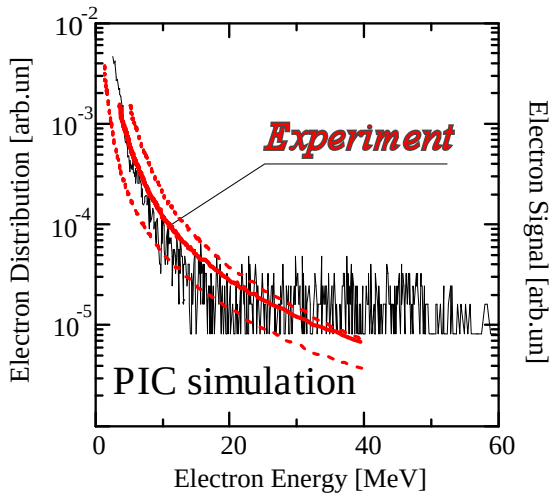




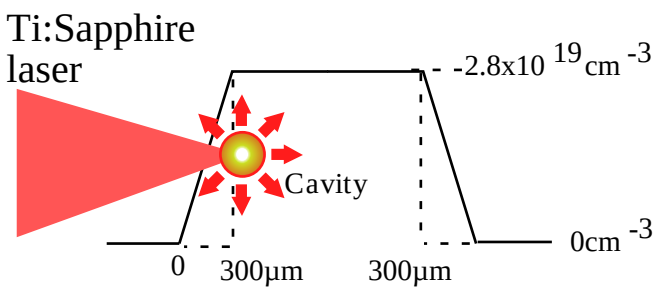
Summary of Prepulse effects -1







Modification of density profile by ns prepulse
(Hydrodynamic motion)

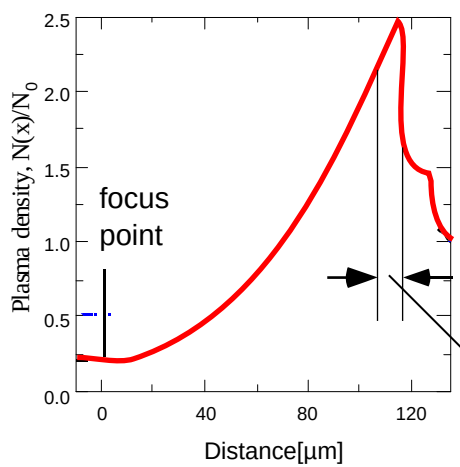


$I_{pre} = 10^{13} Wcm^{-2}$

Rayleigh Length ~50μm

Contrast ratio of
ns Pre-pulse to main pulse 1: ~10^6

Shock



Strong wave breaking @shock front

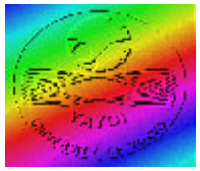
Rapid Injection ~40fs bunch

Plasma wavelength

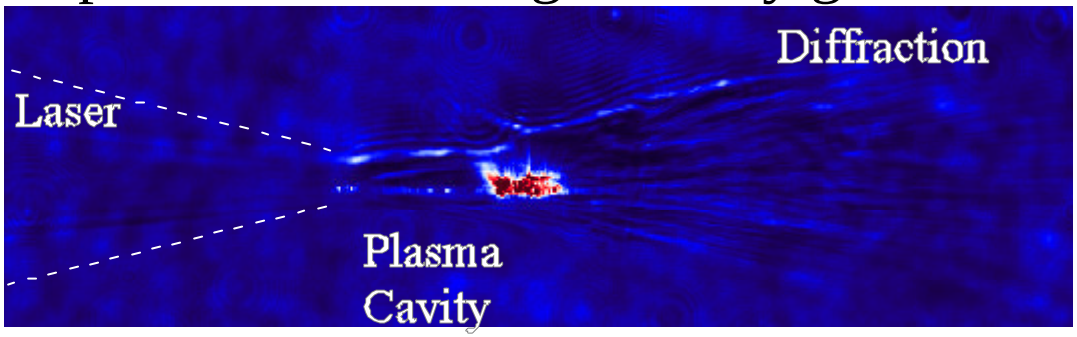
Longitudinal distribution

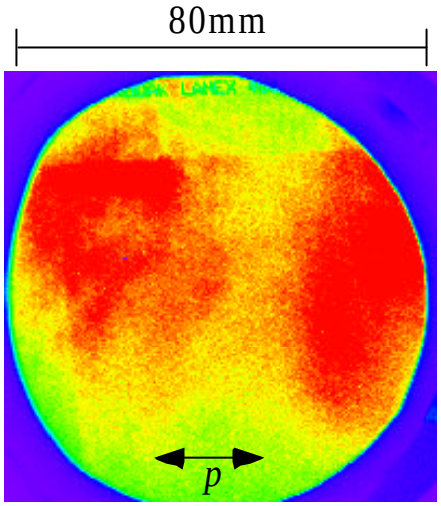
Reference:T.Hosokai,et al.,Phys Rev.E 67,036407 (2003)

Summary of Prepulse effects -2



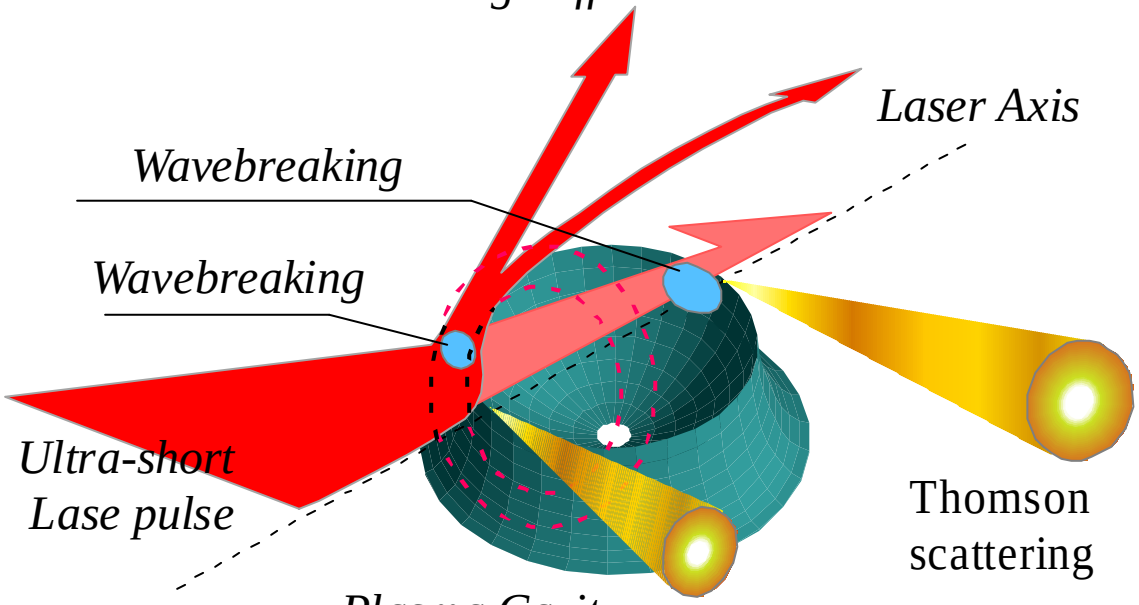
Prepulse effects in high density gas



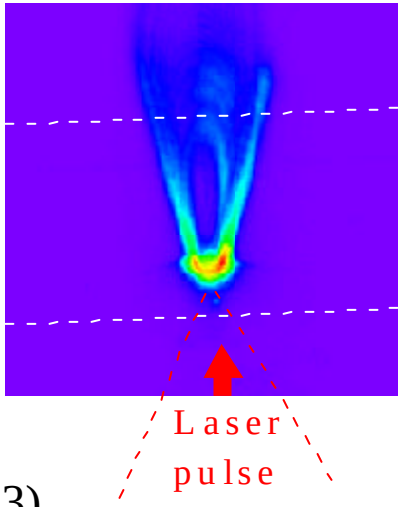


e-spot on LANEX

Strong Diffraction

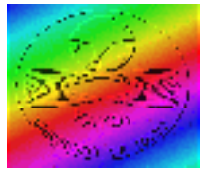


CCD Image of Plasma

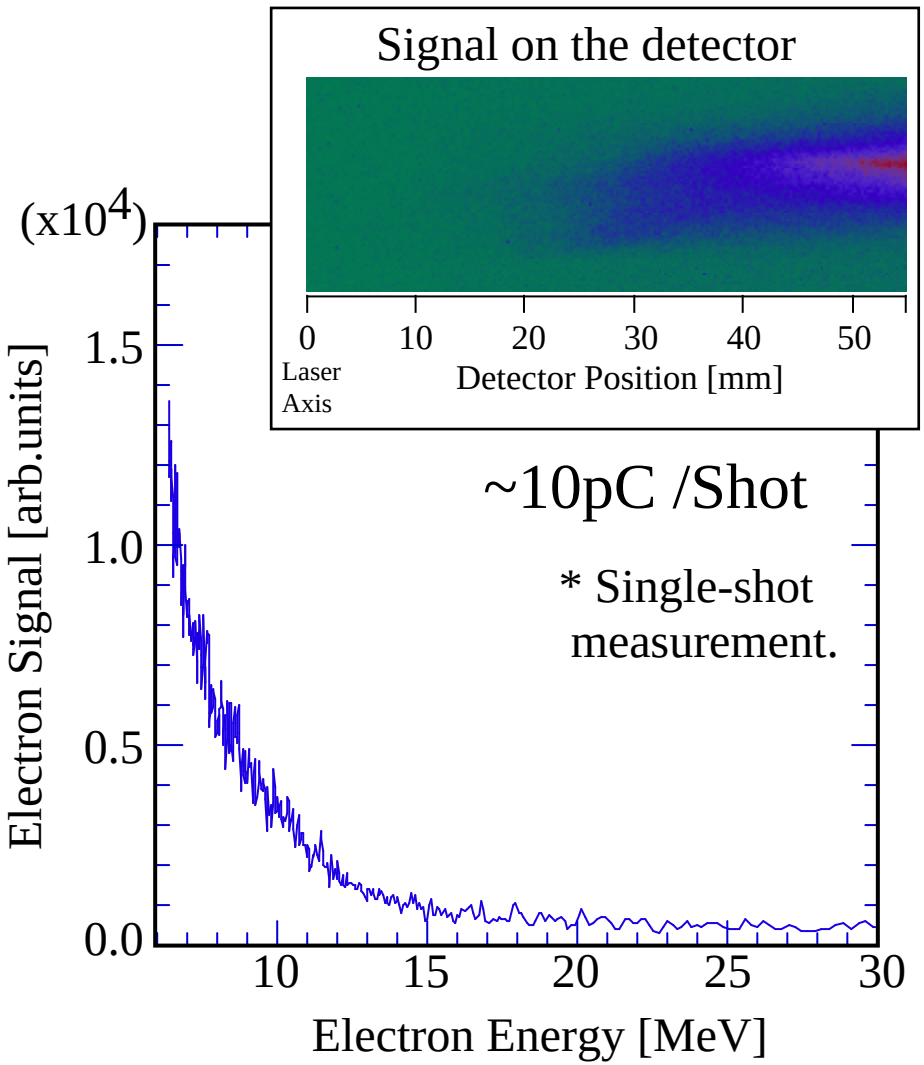


Reference:T.Hosokai,*et al*.,Phys Plasms, 11, L57 (2003)

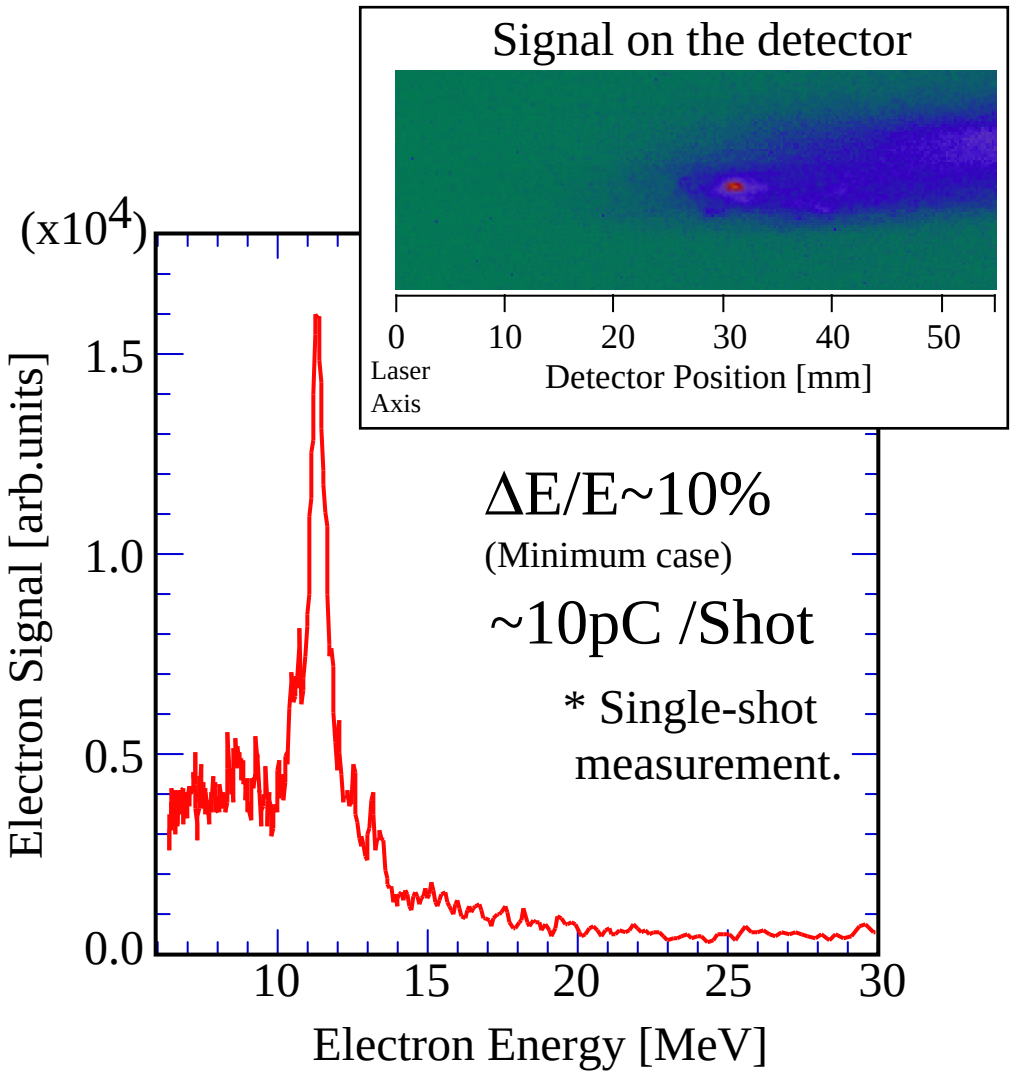
Energy distributions of acceleratedated electrons.



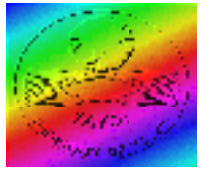
100% Energy spread case



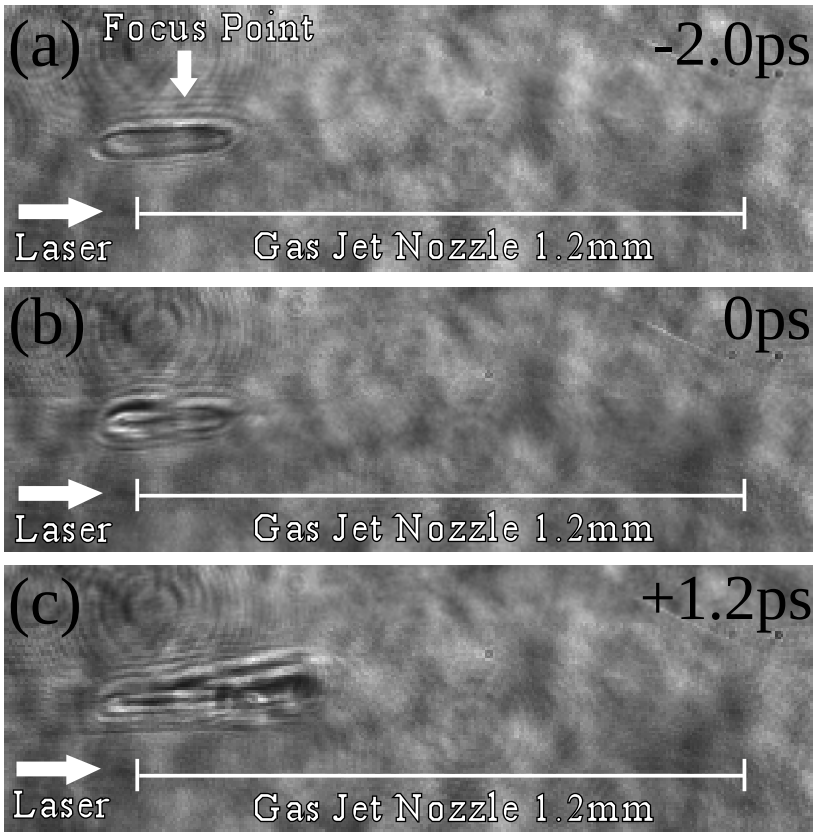
Quasi-mono energy case

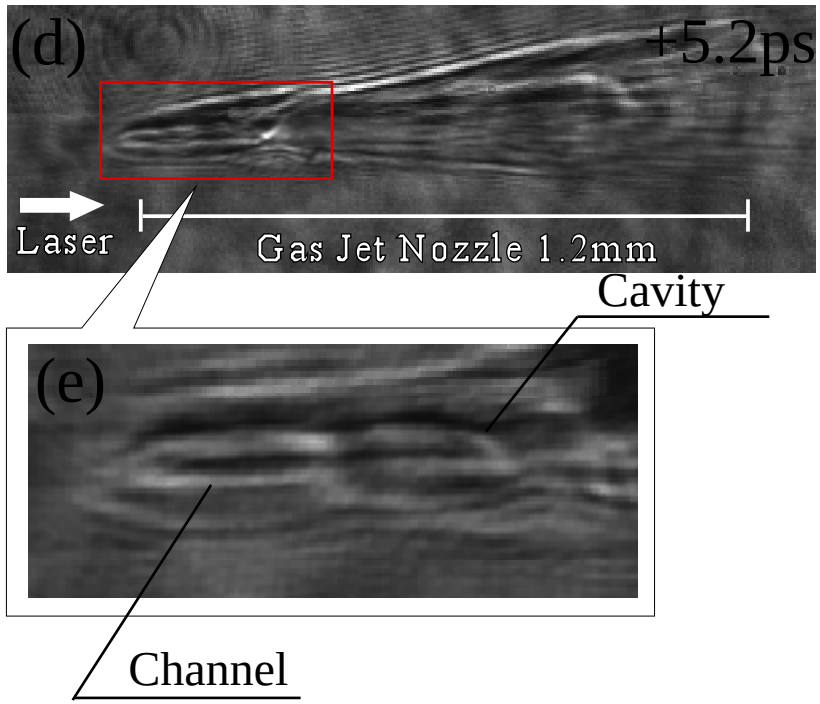


Channel Formation Inside Pre-plasma Cavity



Shadowgraph Images

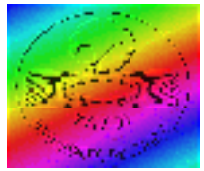




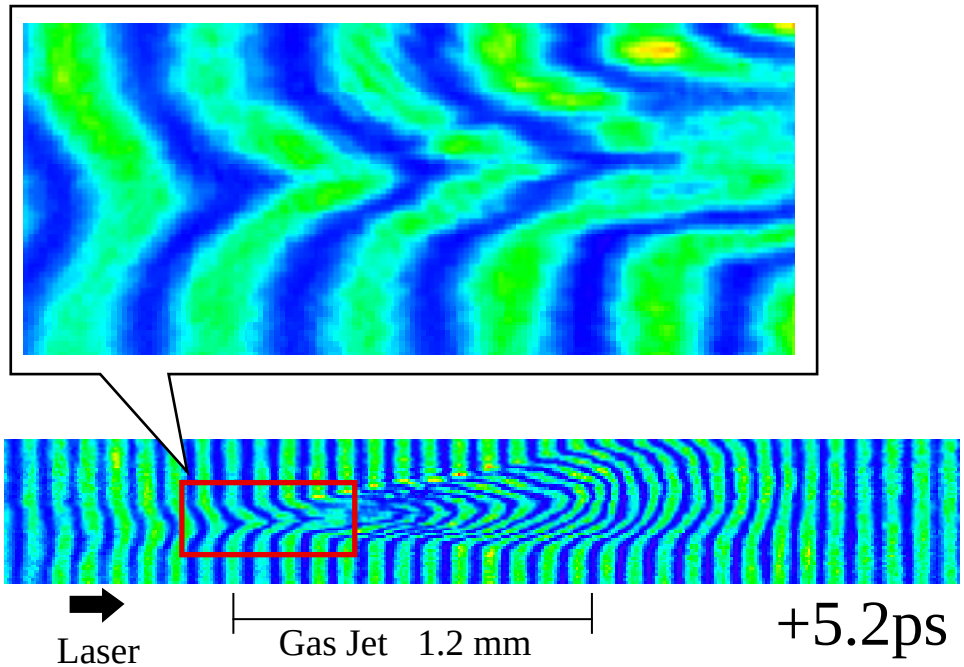
I~11TW (37fs,790nm)
Ne~$4\times10^{19}cm^{-3}$ (Helium)

* Polarization: parallel to the axis of probe pulse.

A Narrow Channel Formation Inside Pre-plasma Cavity

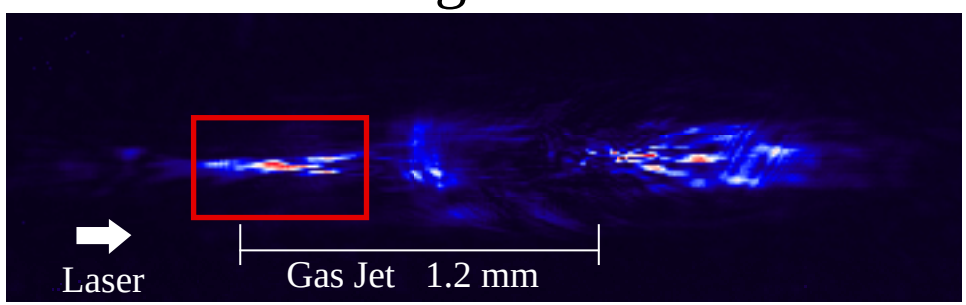


Interferogram



I~11TW (37fs,790nm)
Ne~4x$10^{19}$$cm^{-3}$ (Helium)

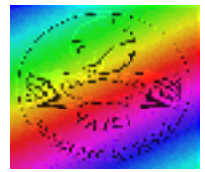
Schlieren Image



+5.2ps

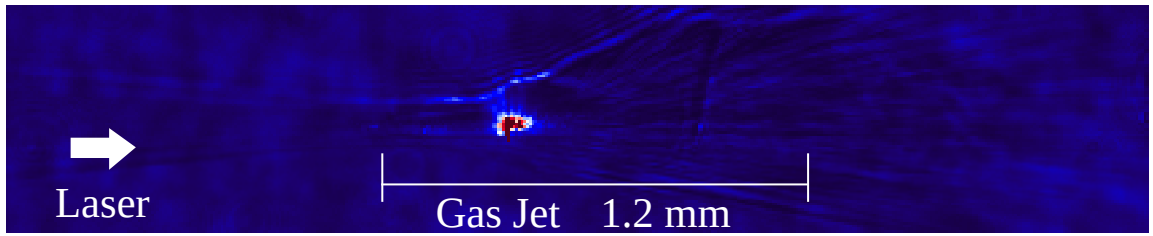
* Polarization: parallel to the axis of probe pulse.

Shadowgraph Images overlapped with Thomson Scattering.



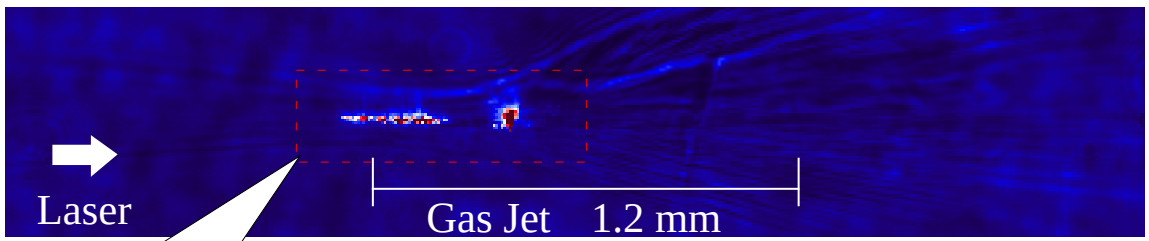
Shadowgraph + Thomson Scattering

100% Energy spread case

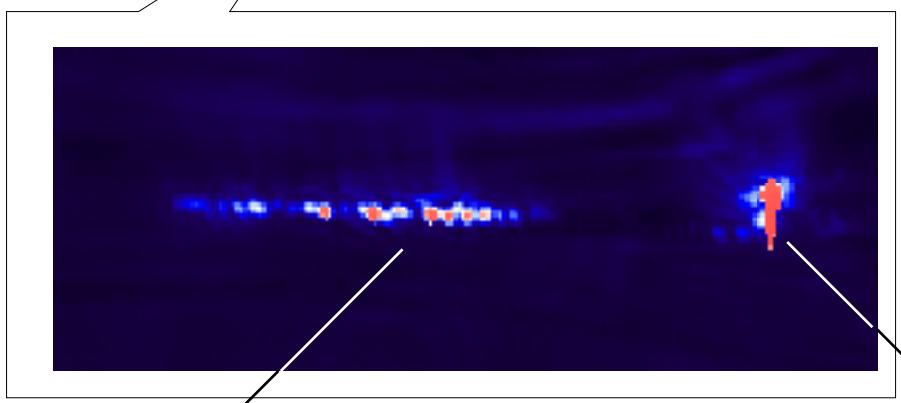


(+5.2ps)

Quasi-mono energy case



(+5.2ps)



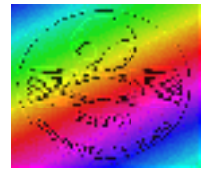
I~11TW (37fs,790nm)
Ne~4x10^{19}cm^{-3} (Helium)

Density ramp by shockwave

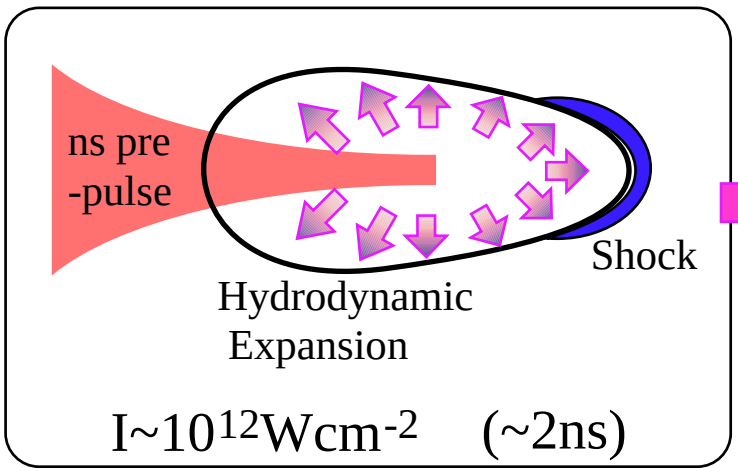
Focus & defocus in the channel

* Polarization: perpendicular to the axis of probe pulse.

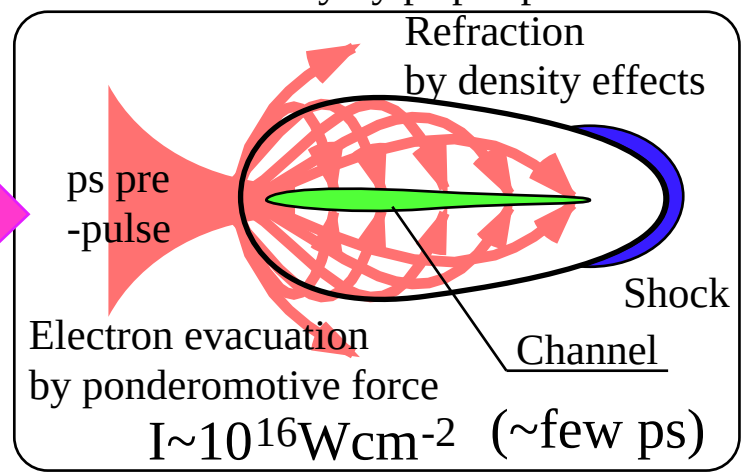
Optical guiding channel formation process



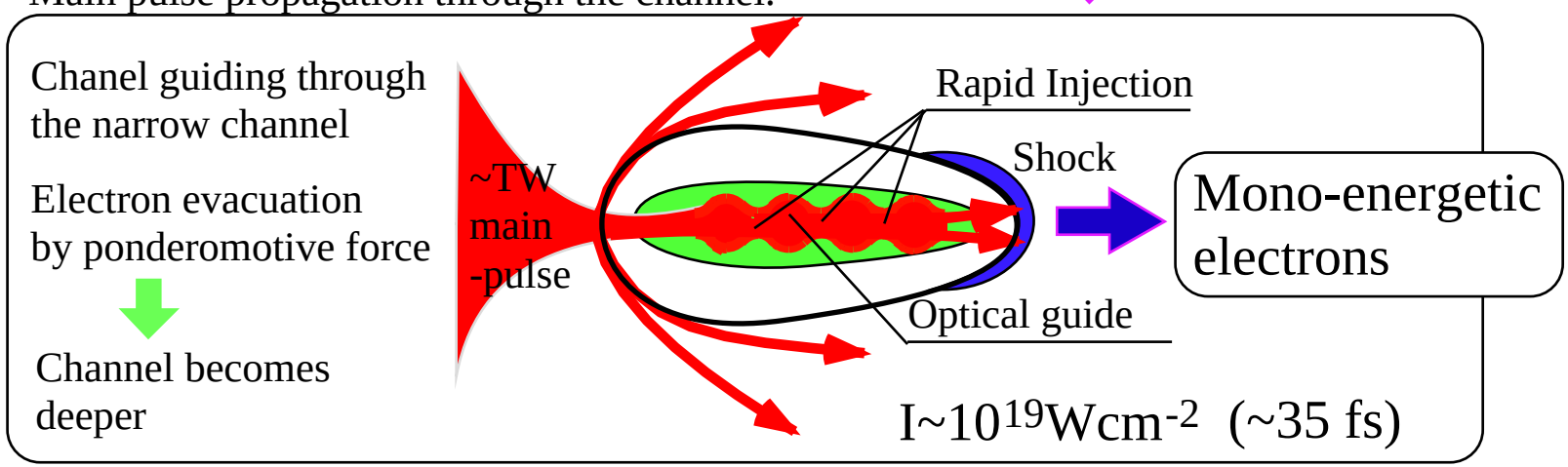
1st Stage
Cavity formation by ns pre-pulse



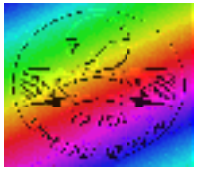
2nd Stage
Narrow channel formation
inside the cavity by ps pre-pulse

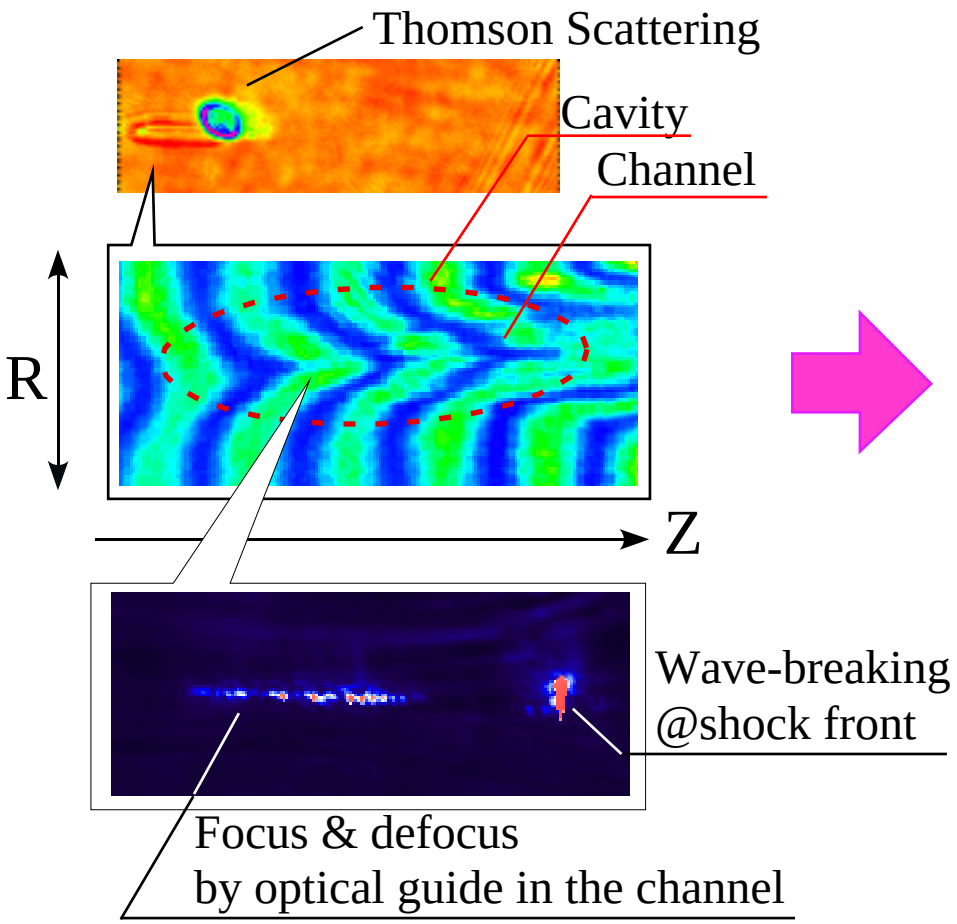


3rd Stage
Main pulse propagation through the channel.

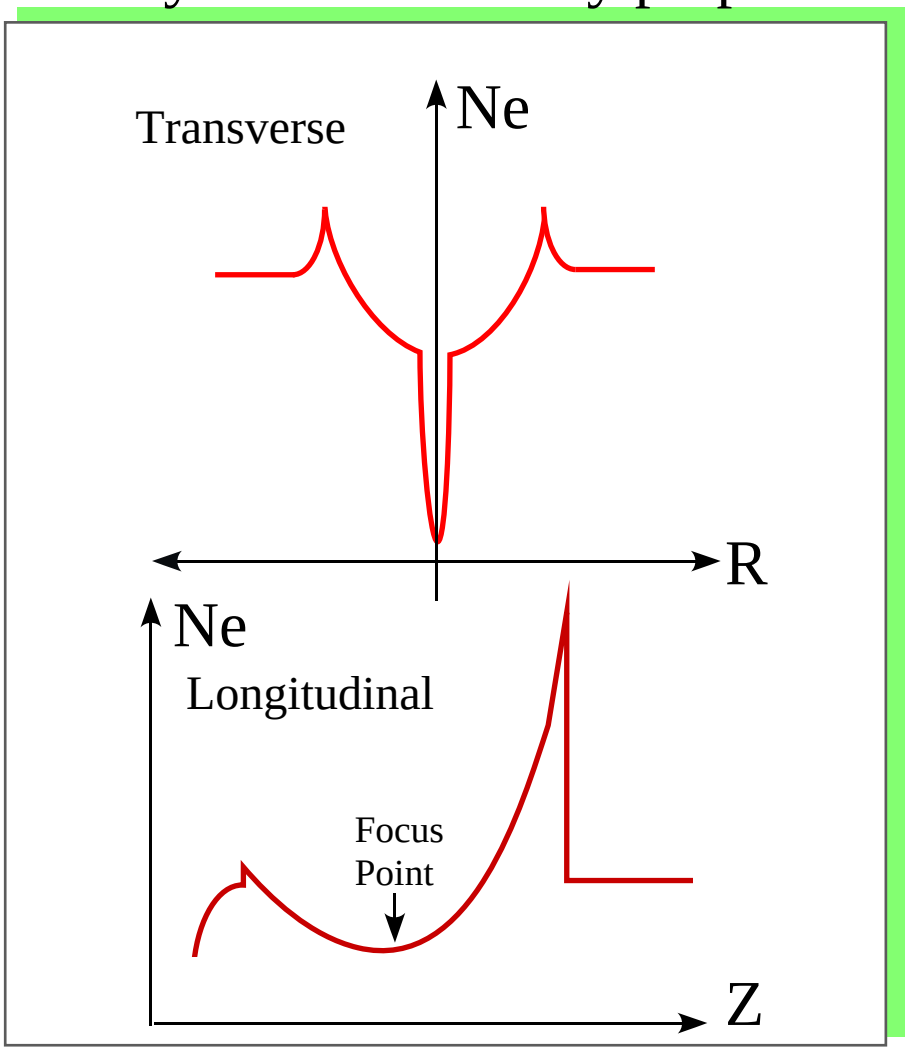


Density structure inside cavity

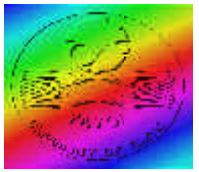




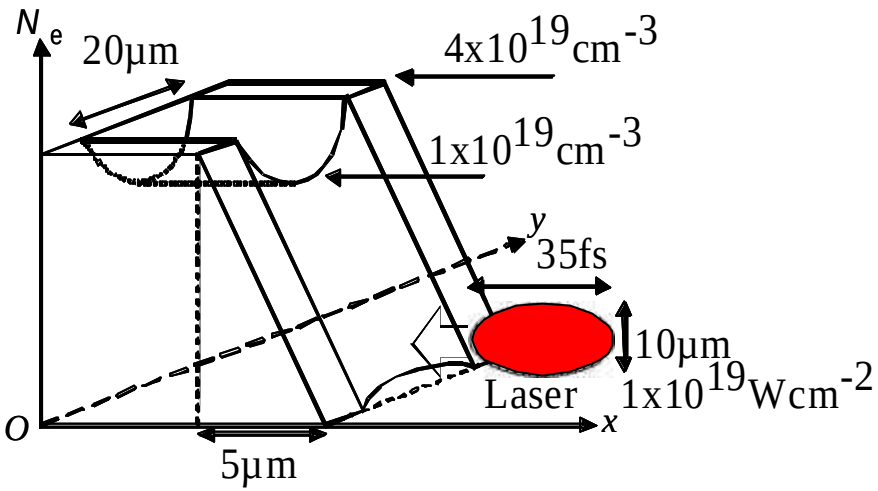
Deisity modification by prepulses

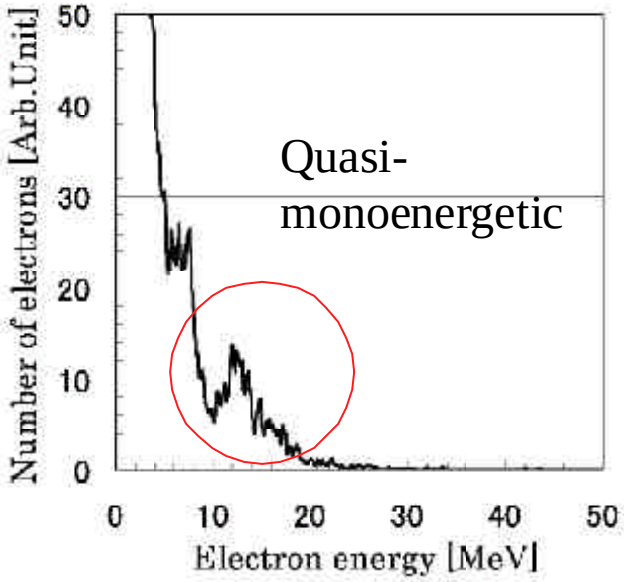


PIC Simulation



Initial density consition
(Preform channel)



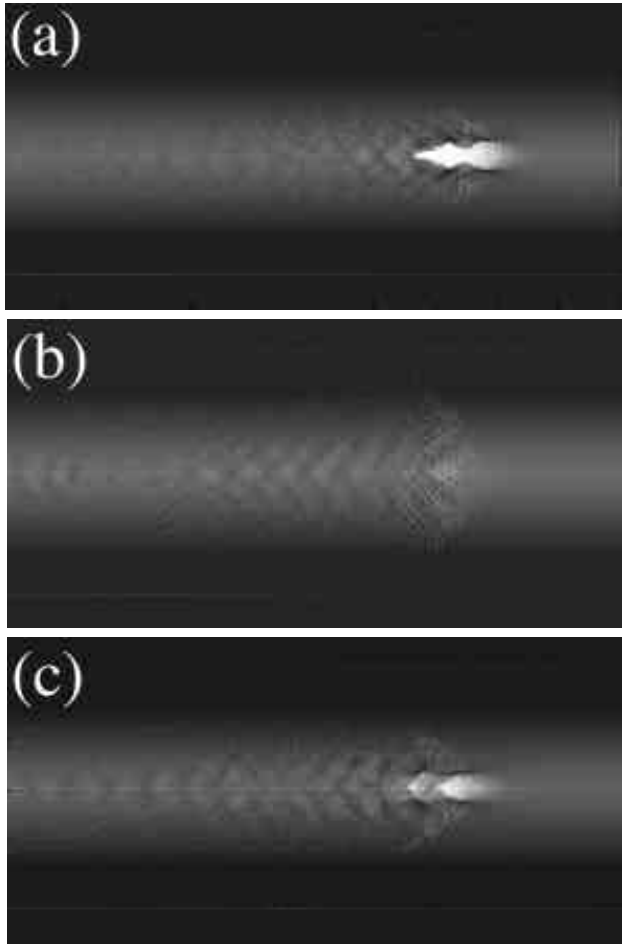


Over focus in a density channel
& Rapid injection by wave breaking

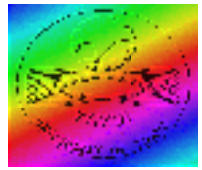
Focus
&
Wave
breaking

Defocus
&
Regular
wakefield

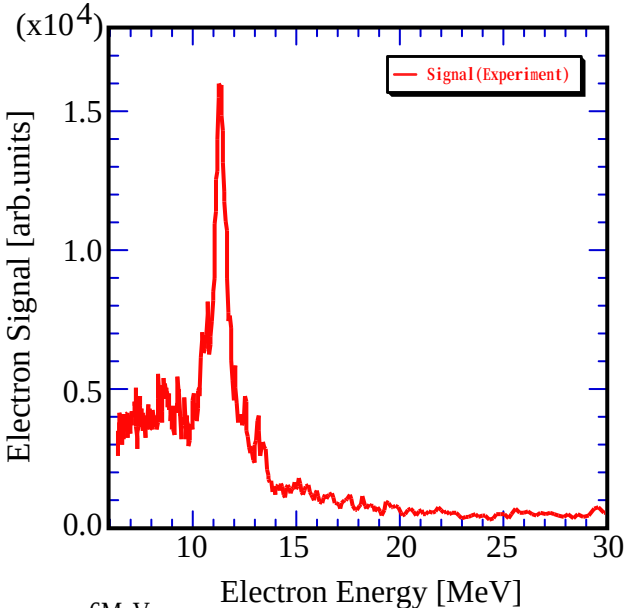
Focus
again



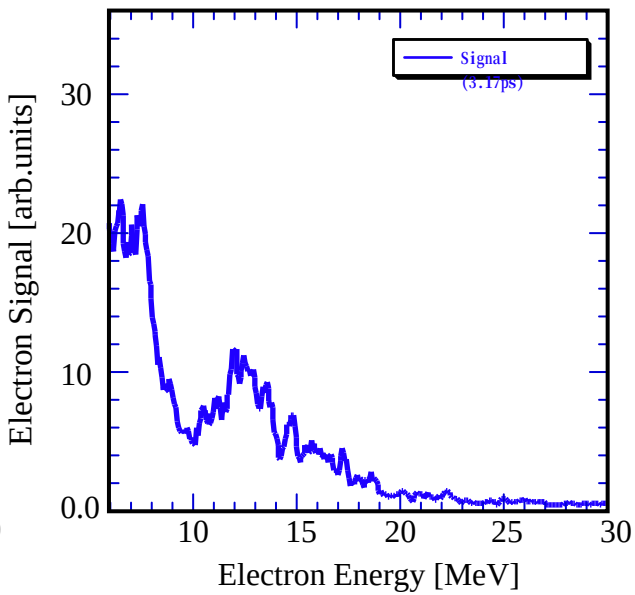
Energy Spectra, (Experiment and PIC Simulation)

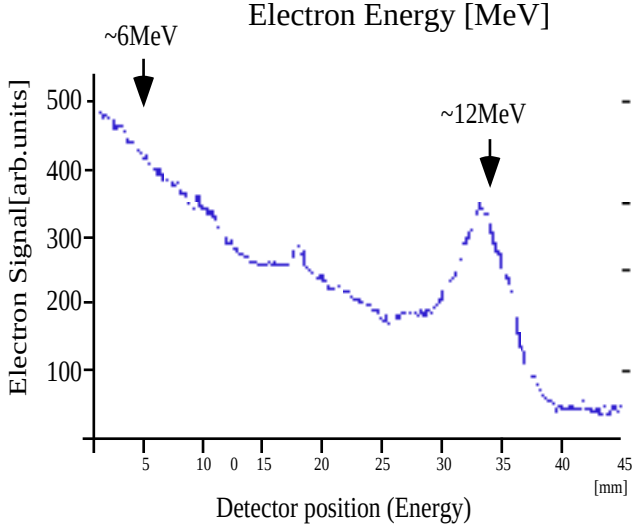


Single-shot spectrum



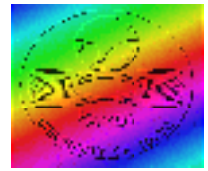
PIC Simulation



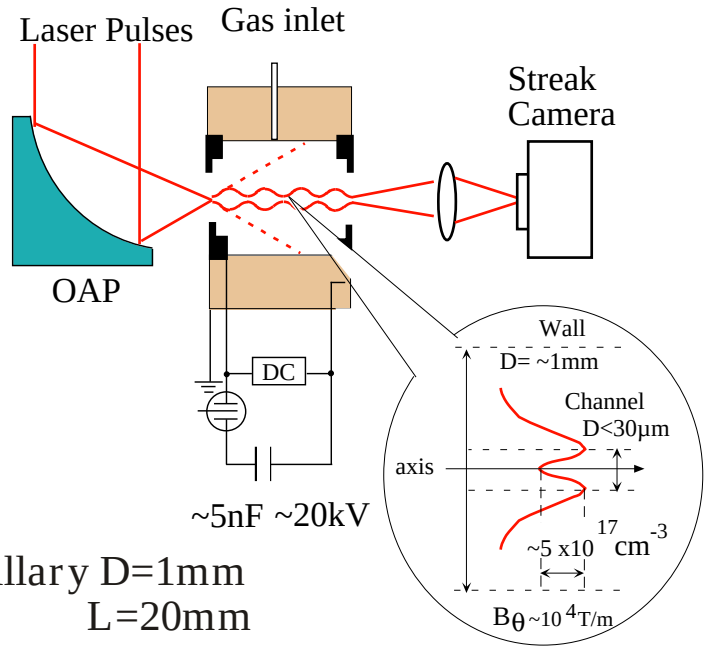


5-shot accumulated spectrum

Further acceleration by capillary discharges, Optical guiding by Fast Z-pinch discharges



Long Plasma Channel
by Fast Z-pinch discharges in capillary



Capillary D=1mm
L=20mm

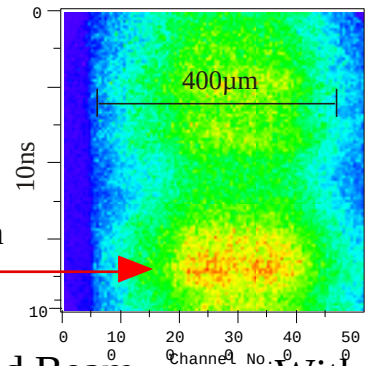
Plasma Channel
D=30~70μm

Typical e-density profile in the plasma column produced by fast Z-pinch.

Plasma channel parameters
can be controlled by discharges

Ref. T.Hosokai et.al,Opt.Lett.25,10(2000)

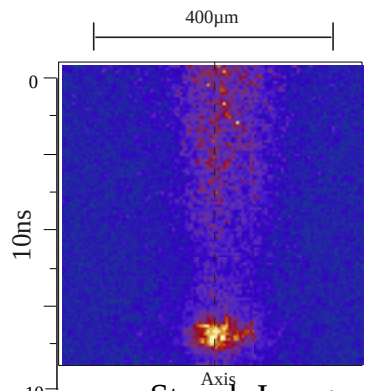
Streak Image of Discharge



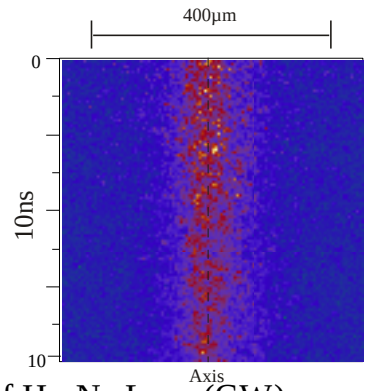
He 1Torr
4.8kA D = 1mm

Channel Formation
@8.5ns

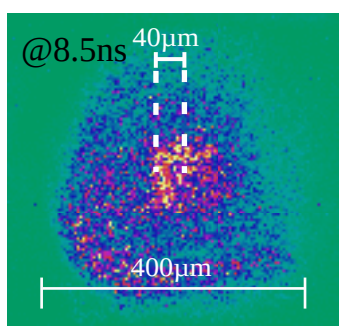
Guided Beam

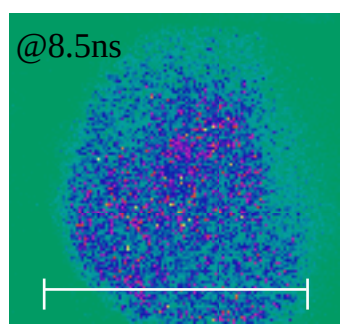


Without Guide



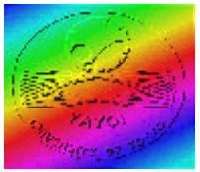
Streak Images of He-Ne Lase (CW)





Gate CCD Images of Ti:sapphire Lase pulse

Summary



2-staged acceleration using a gas-jet injector with capillary discharges is one of the most promising approach to produce high quality electron bunch with tens MeV, tens fs, and quasi-mono energetic distribution.

Injector -- Laser plasma cathode

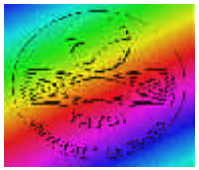
- Cavity formaton & Density steepening
  - ➡ Expanding shock by ns pre-pulse
- Narrow channel Formation inside the cavity
  - ➡ Focusing of ps-pulse due to density effects inside the wall ?
- Optical guiding through pre-channel inside the cavity

Quasi-mono energetic electrons by LWFA

Next Step

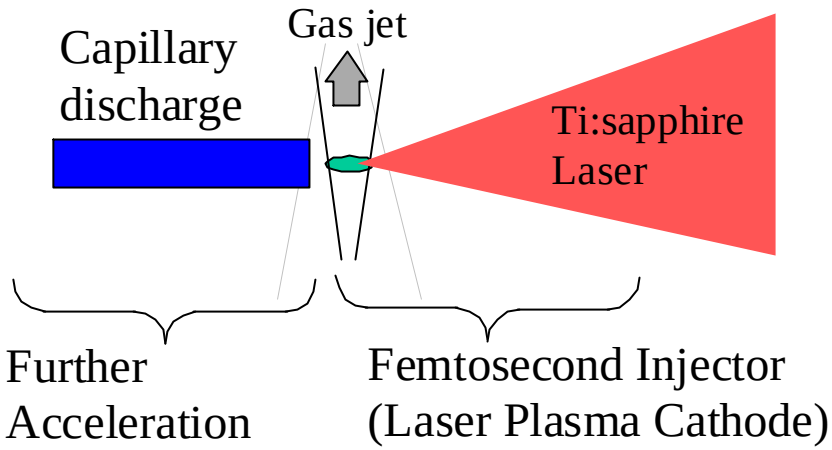
➡ Further acceleration using capillary discharges.

Approach to quasi mono-energitic femtosecond electron bunch



Staged Acceleration

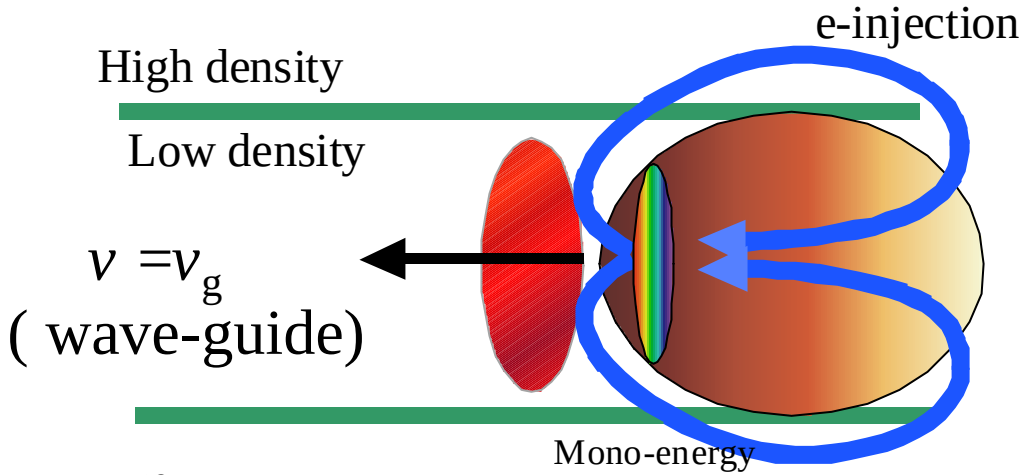
- A plasma channel can serve as a media for perfect wake-field for further acceleration generated via wave-breaking



Selfinjection

- To make self-injection the cavity length should be longer than the pulse length $d=\lambda_p a_0 > c\tau$ and

$$v_g \le c\sqrt{1-1/\gamma^2} \;;\gamma = 1+a_0^2/2$$



Self-injection is possible for
a laser pulse with τ=50 fs and intensity I=10^{19} W/cm^2
in a wave-guide with diameter D~100-200 μm

$$E_{emax} = mc^2 a_o^2/2$$

A. Zhidkov, et.al Phys. Rev. E **69**, 035401(R) (2004)