June 26, 2004
International Symposium on
Ultrafast Accelerators for Pulse Radiolysis

Laser plasma cathode by 12 TW, 50 fs laser and its application to radiation chemistry

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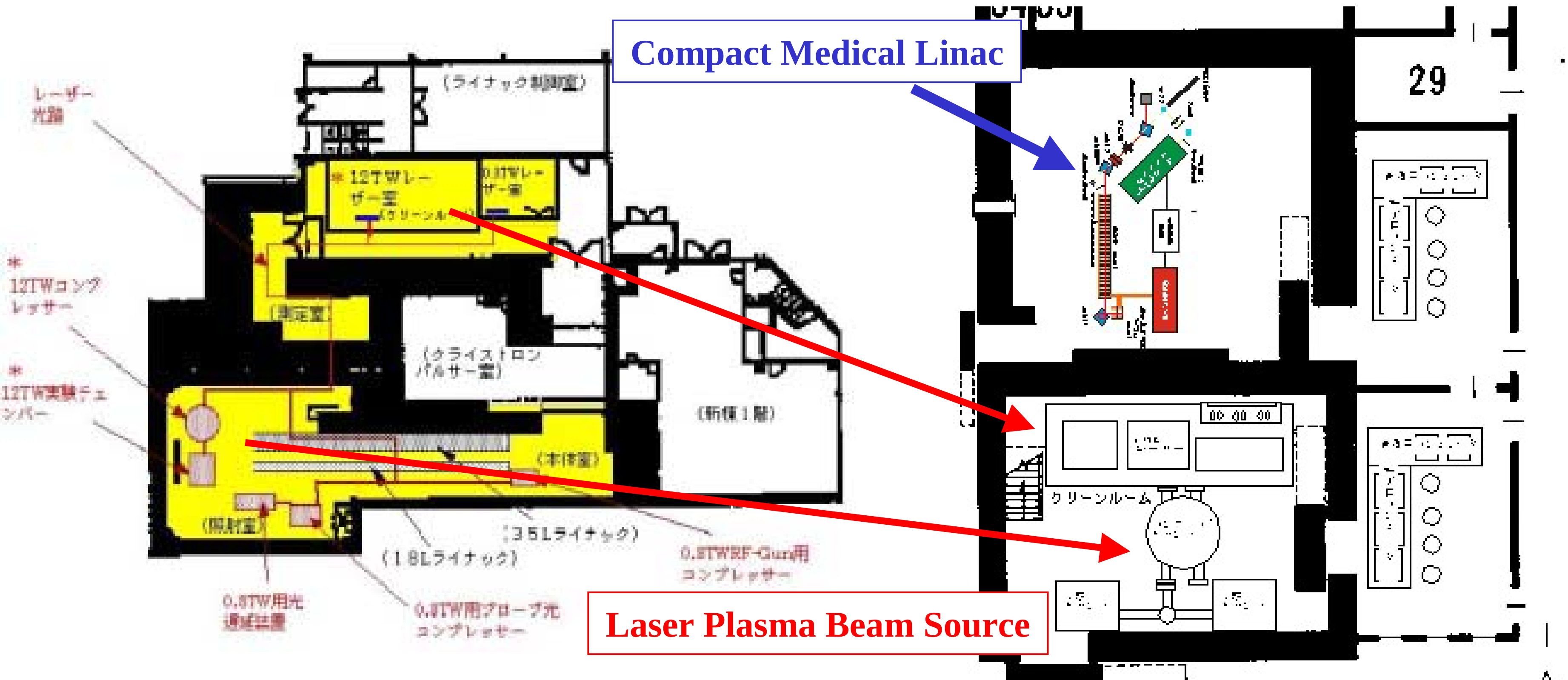
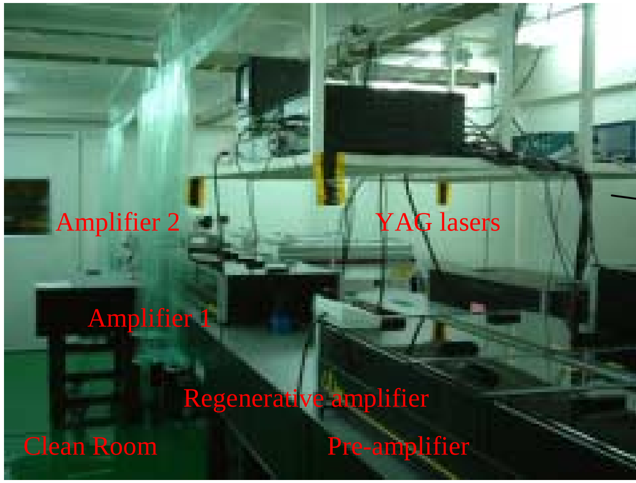
Two New Accelerator Rooms
Compact Medical Linac/Laser Plasma Beam Source



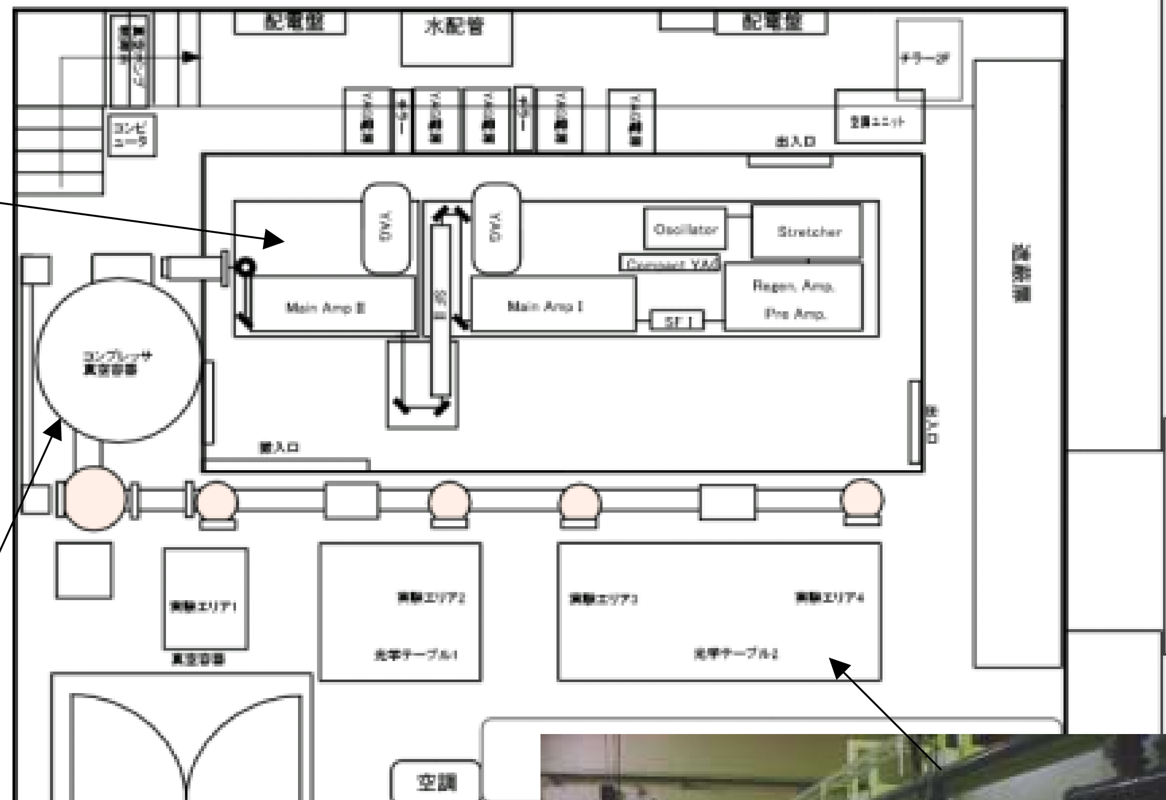
Linac Building(1st Floor)

Fusion Blanket Building (1st Floor)

12TW 50fs Laser Plasma Beam Source



Laser system



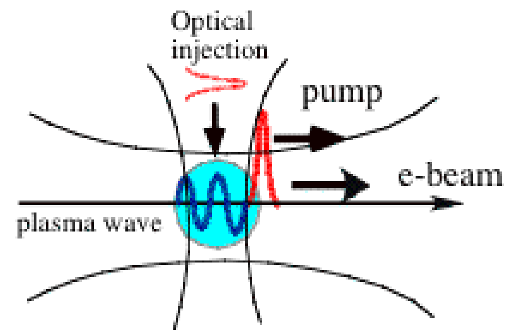
Compressor chamber

Experimental area

Optical Injection Methods

- Ponderomotive injection from single pulse
  - Injection pulse intersects wake from pump at 90^0
  - Ponderomotive force injects electrons
    - Umstadater et al., PRL 96
    - Hemker et al., PRE 98

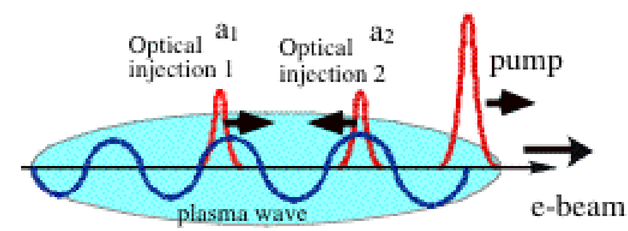
$$F_z \propto \nabla a_1^2 \propto a_1^2 / r_1$$



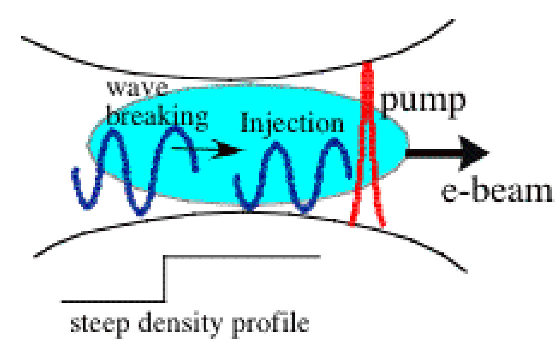
- Beat wave injection from colliding pulses
  - Two counterpropagating injection pulses collide
  - Injection from beat wave with slow phase velocity
    - Esarey et al., PRL 97
    - Schroeder et al., PRE 99

$$F_z \propto \nabla a_1 a_2 \propto a_1 a_2 / \lambda_0$$

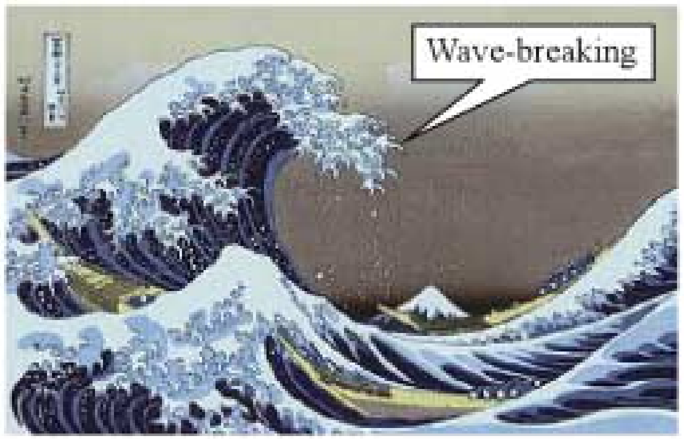
$$v_{ph} \approx \Delta\omega / \Delta k \approx \Delta\omega / 2k_0 << c$$



- Downward density transitions
  - Wake phase velocity decreases on down ramp
  - Wavebreaking induced some distance behind pump
    - Bulanov et al., PRE 98
    - Suk et al., PRL 01



Electron Injection by Plasma Wave Breaking



- ***Wave-breaking field***

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

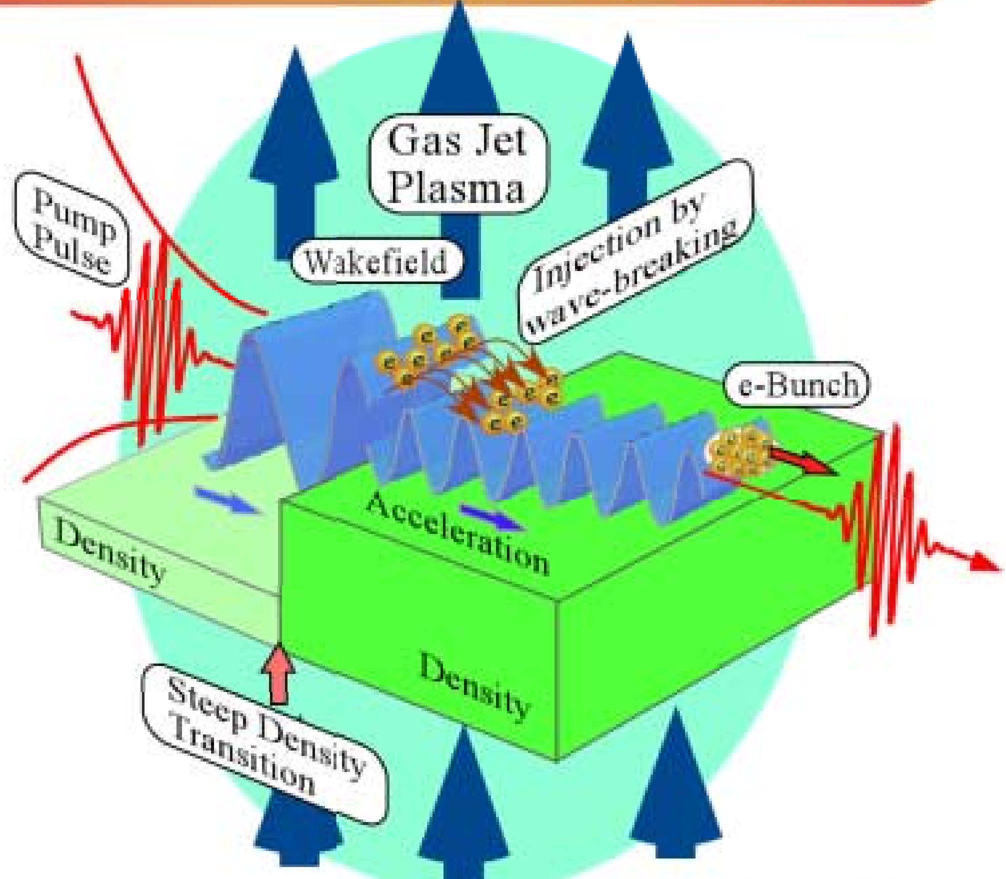
- ***Density gradient***

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

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

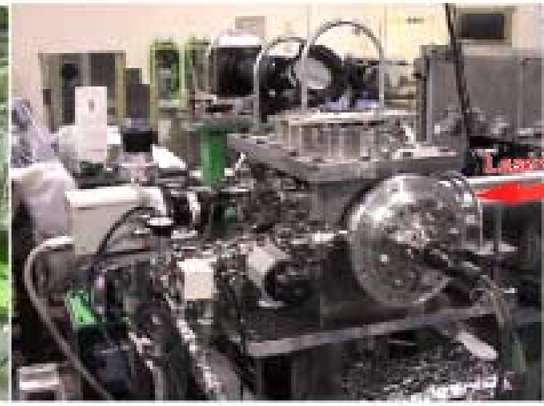
Femtosecond electron bunch generation

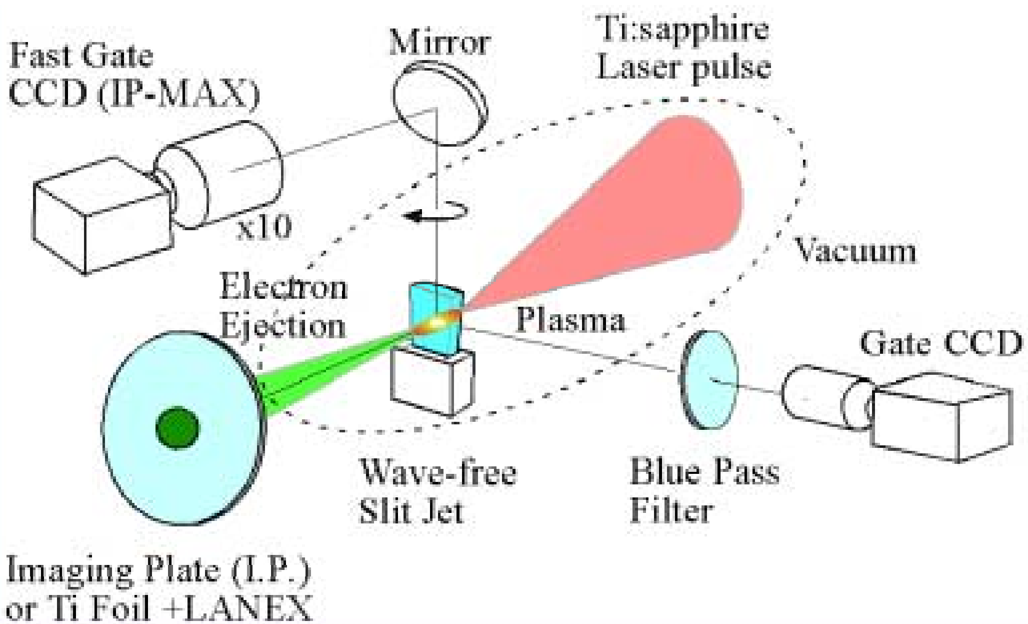
Proper injection into correct acceleration. phase of wakefield



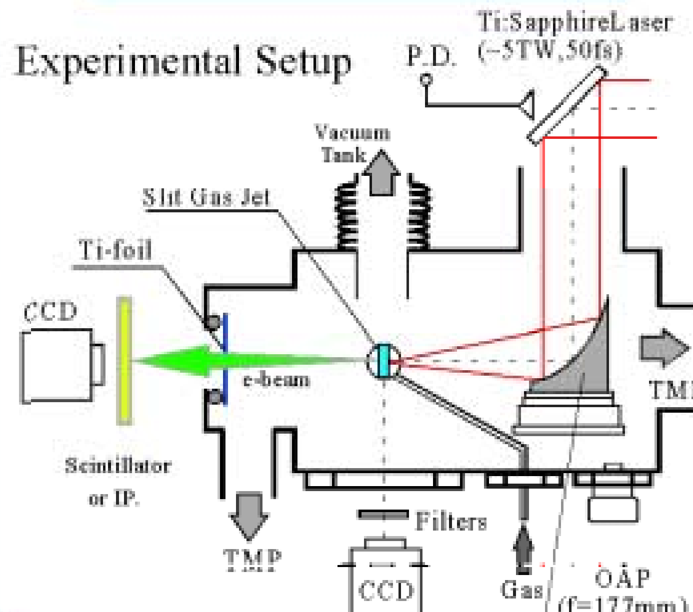
Reference : S.V.Bulanov, et al, Phys.Rev.E. 58, R5257

Experimental Set-up



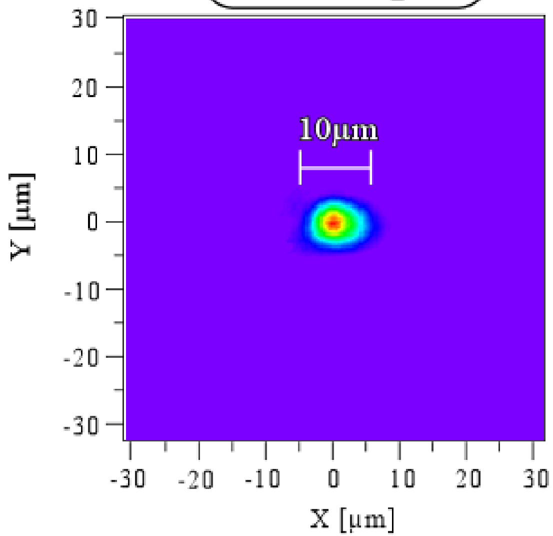


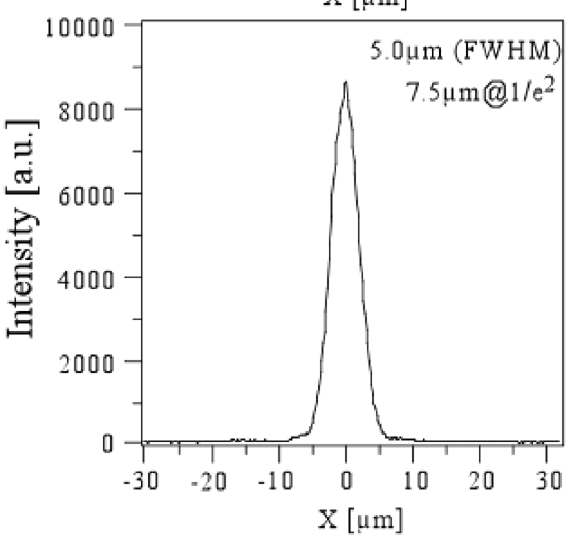
Inside Chamber



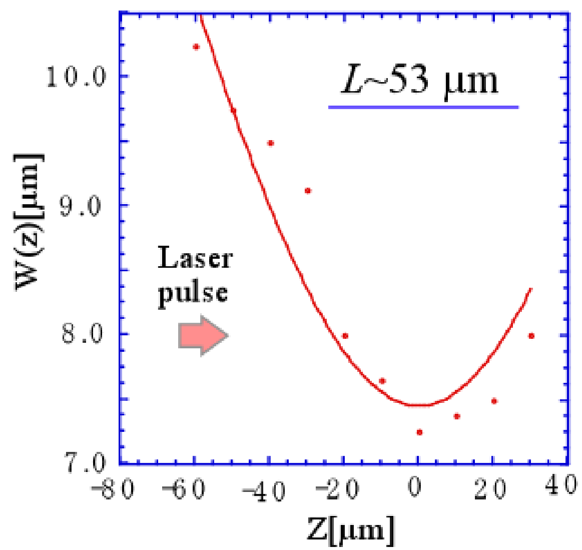
Laser Spot Measurement

Laser spot

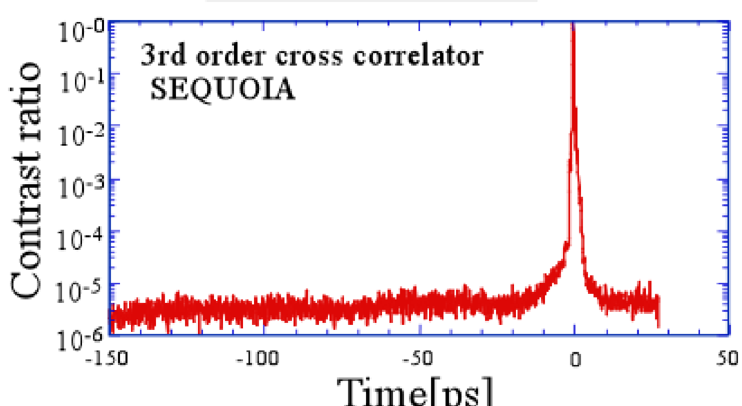




Rayleigh Length



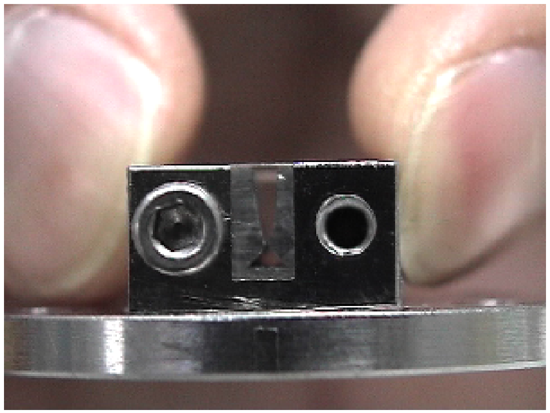
Contrast Ratio

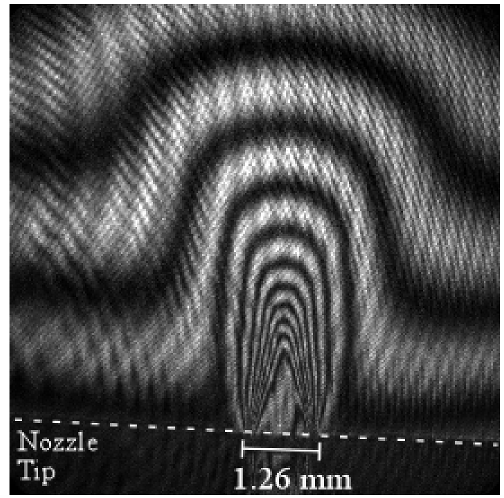


Focusing Parameter

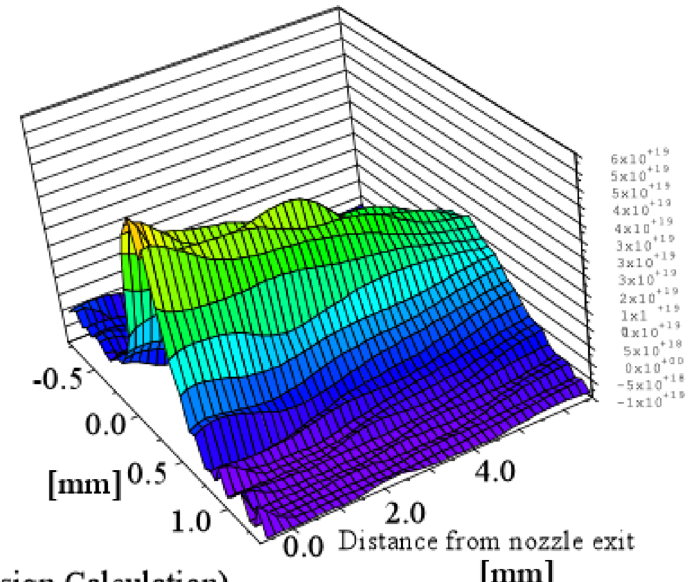
- OAP f=177mm
- Beam size D~50mm
- $F^{\#}$~3.5
- Spot size ~7.5 μm @1/e^2
- Rayleigh length ~53 μm
- Power Density for Main Pulse (~5TW) ~1.0×10^{19}Wcm^{-2} a_0~2.0
- Contrast Ratio 1:1×10^{-6}
- Power Density for Pre-pulse ~1.0×10^{13}Wcm^{-2}

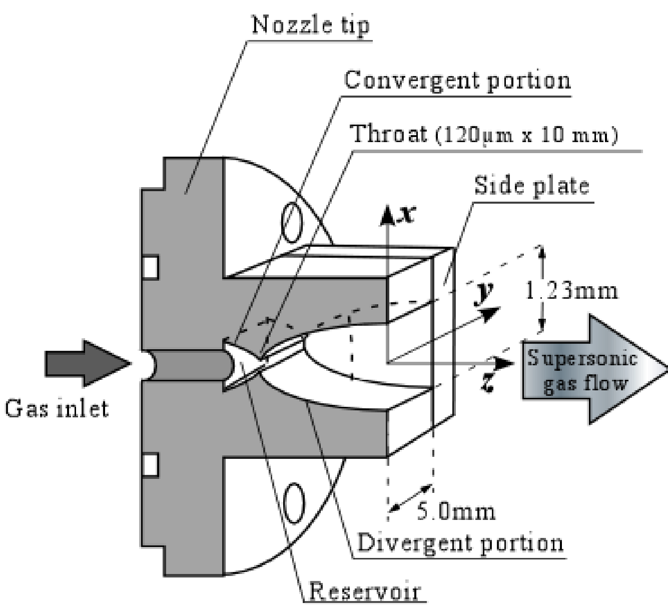
High-density well-defined gas jet (1)
Shockwave free supersonic nozzle



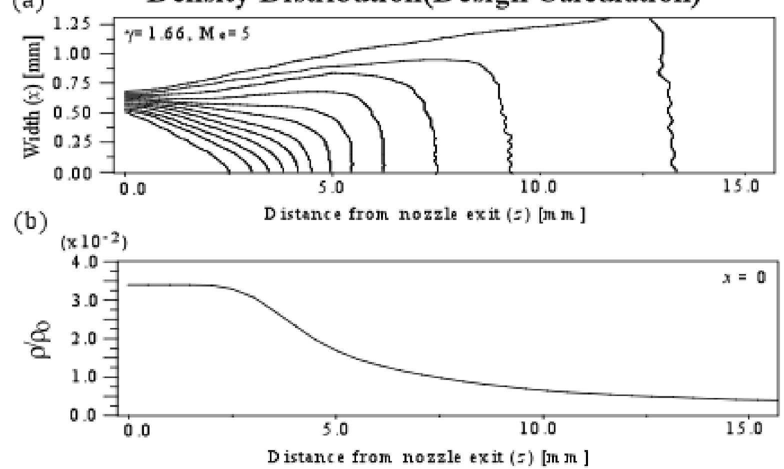


Measured Density Distribution





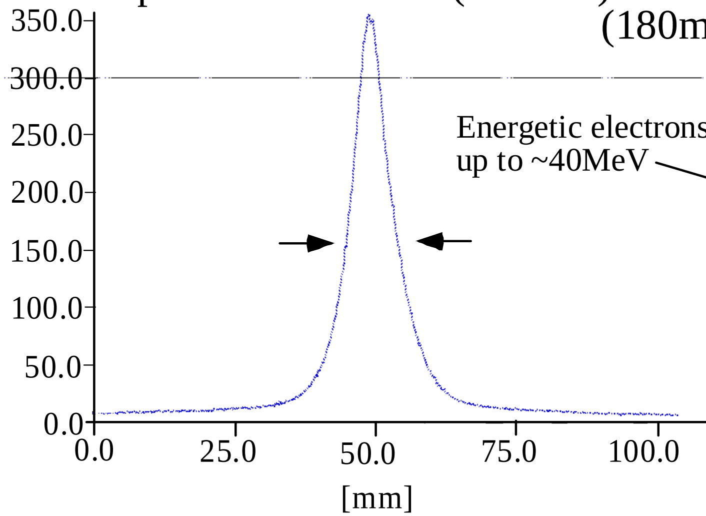
Density Distribution(Design Calculation)



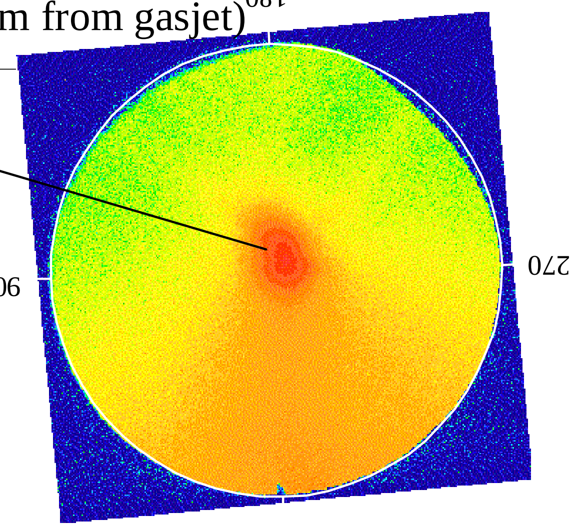
Typical Image of Electron Beam Generation (Experimental Results: Signals on I.P.)

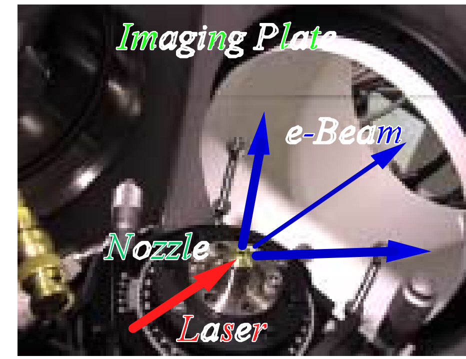
He 2.8x10^{19}cm^{-3}, Laser ~4.8TW

Spotsize D~8.1mm (FWHM)

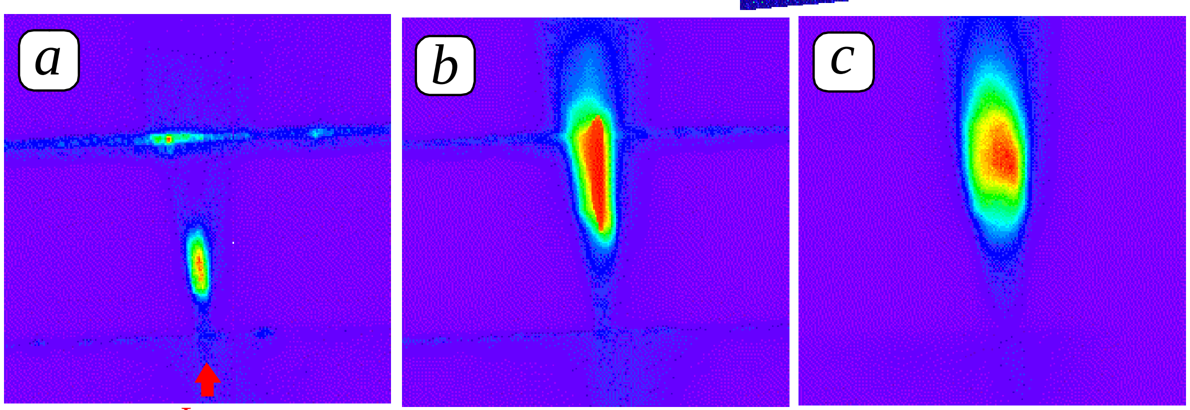


(180mm from gasjet)





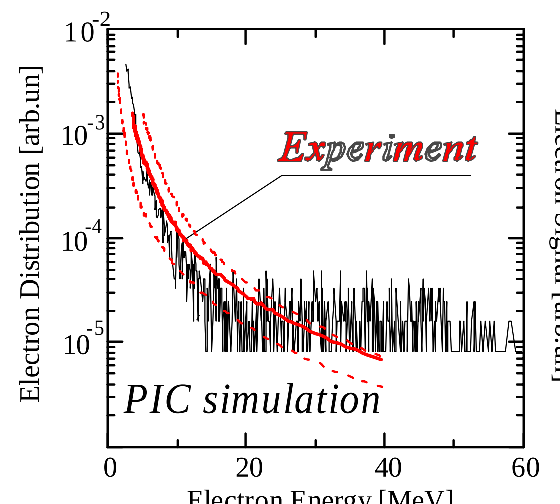
Experimental Set-up



-1~1ns (Main Pulse)

b: 1ns~3ns

c: 2ns~5ns

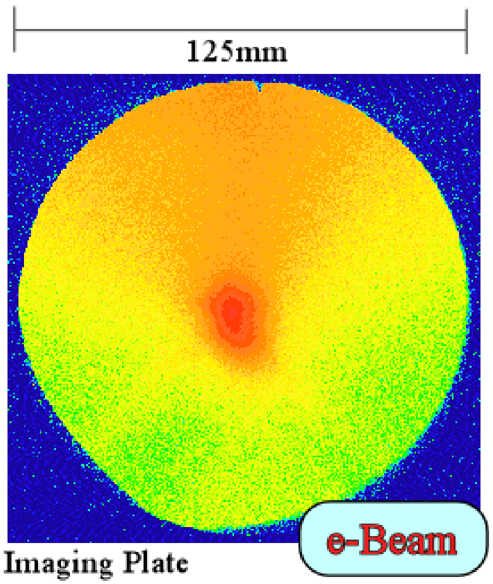


e-spectrum

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

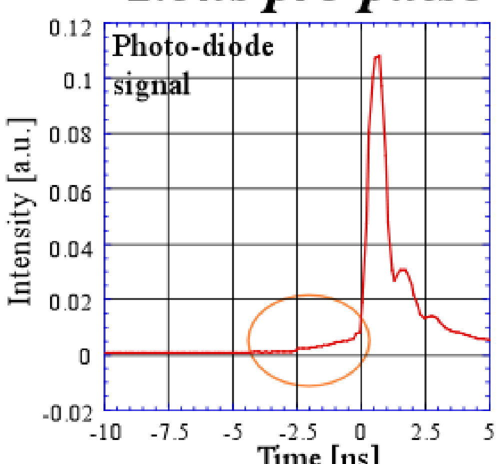
Laser Pre-pulse Effect on Ejection of Energetic Electrons from Gas-Jet (Typical 3 Cases)

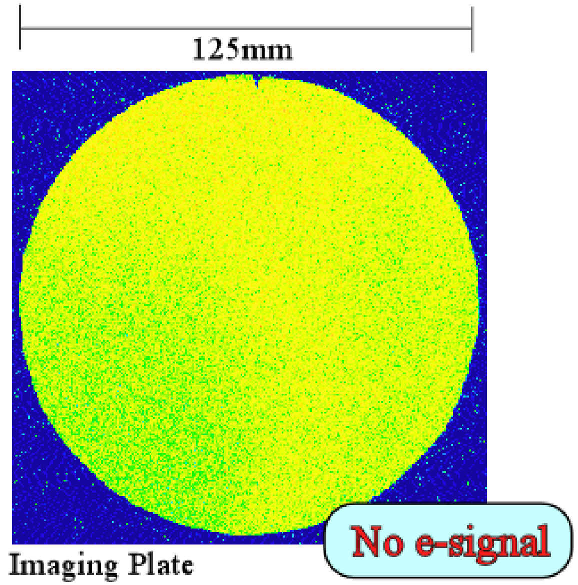
(He 2.8×10^{19}cm^{-3}, Laser 4.8TW)



Imaging Plate

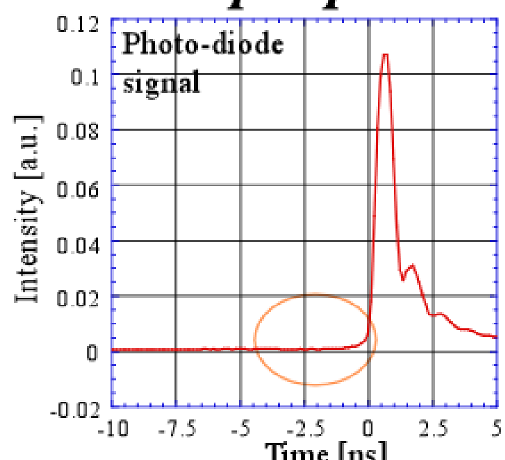
~2.5ns pre-pulse

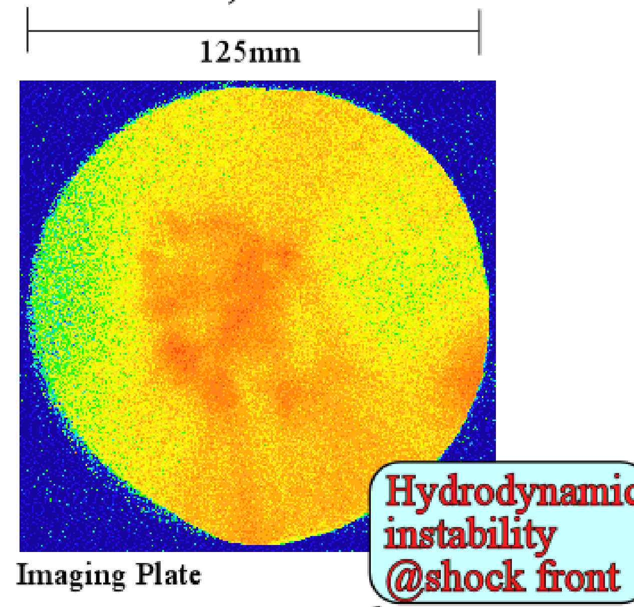




Imaging Plate

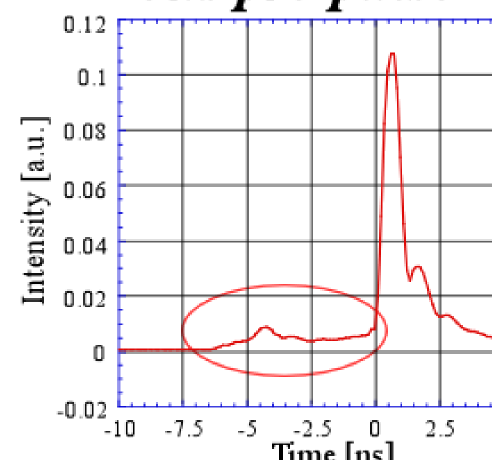
~1ns pre-pulse





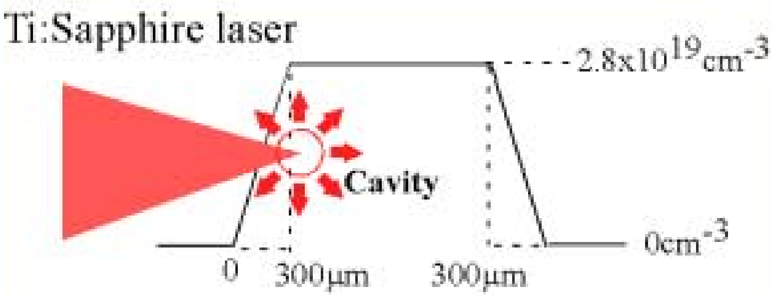
Imaging Plate

~ 5ns pre-pulse



Laser Pre-pulse Effect (Hydrodynamic Simulation Results)

Initial density profile of He gas-jet

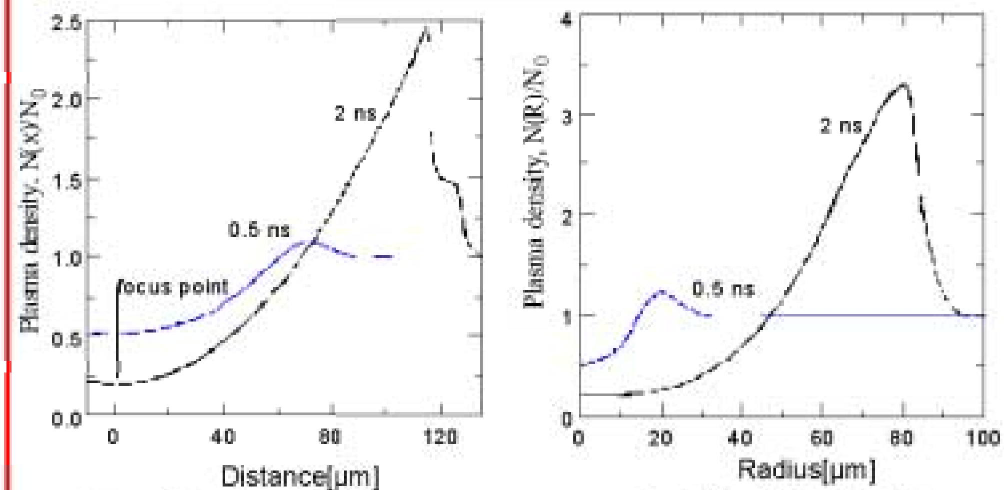


$I_{pre} = 10^{13} \mathrm{W cm^{-2}}$

Rayleigh Length ~50μm

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

Density Profiles of He-jet after the laser pre-pulse



Longitudinal distribution   Radial distribution

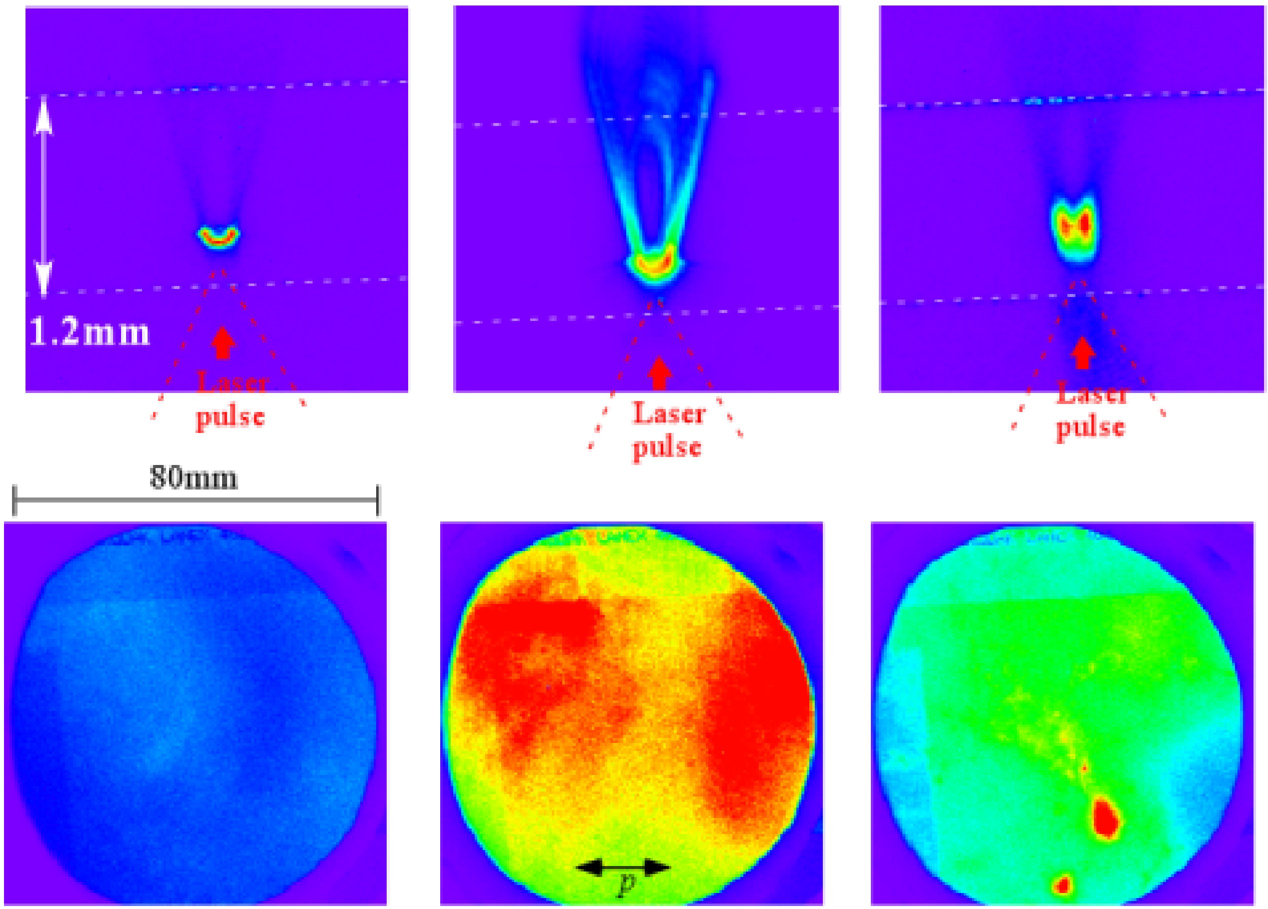
In our case (for **Short Rayleigh length Optics** ; contrast to LULI, LOA Group)

- **Cavity formation**
- **Density steepening by shock wave**

< 1 ns No Injection	→	No signal
2~3 ns Injection by Wave-breaking	→	Single peak spot
> 5 ns Hydrodynamic instability	→	Exploded spots

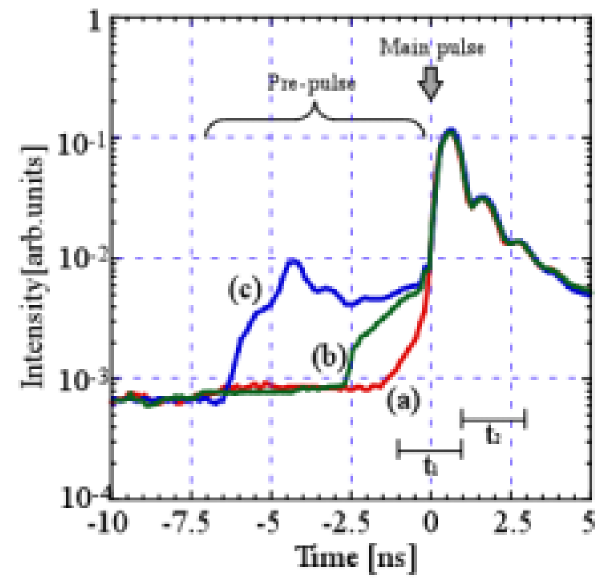
Pre-pulse Effect in High-density Plasma

Cavity Formation Depends on Pre-pulse



e-spot on LANEX

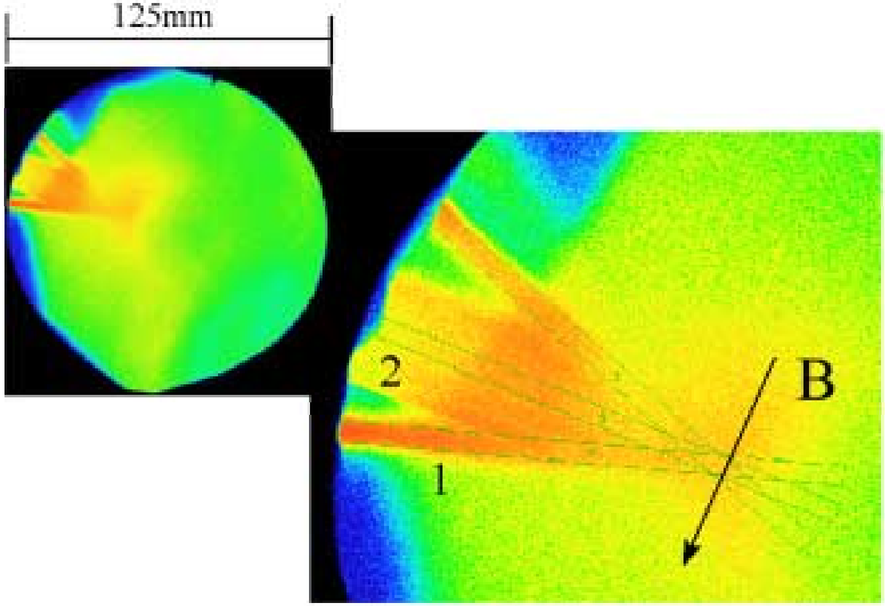
$4.5 \times 10^{19} cm^{-3}$ of He

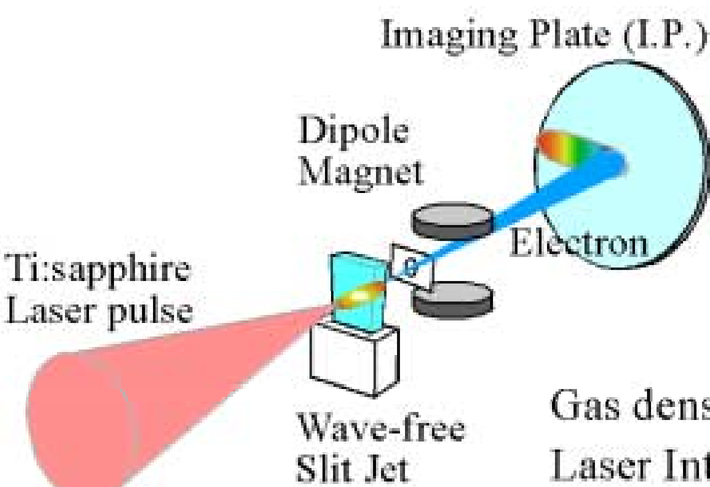


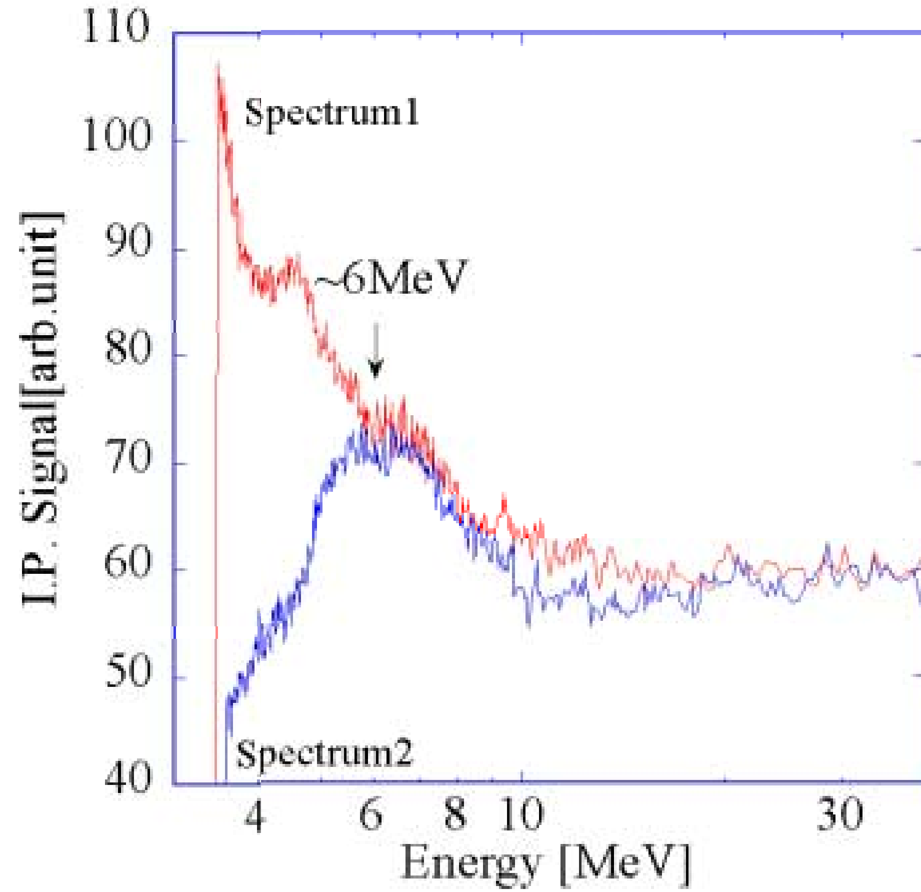
Reference:T.Hosokai,*et al.*,Phys. Plasmas (In press 2004)

Ejected e-Beam has a spatial structure?

Quasi-mono-energy distribution ???

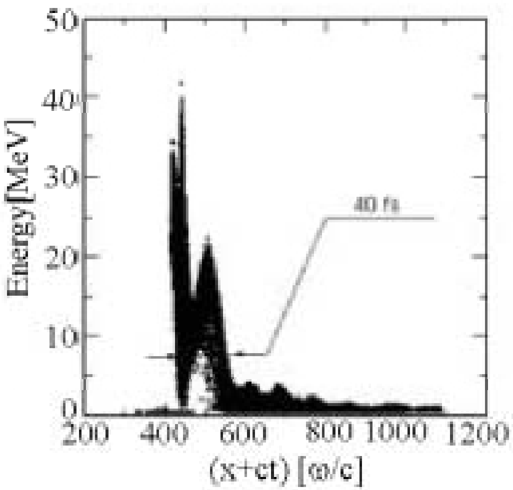






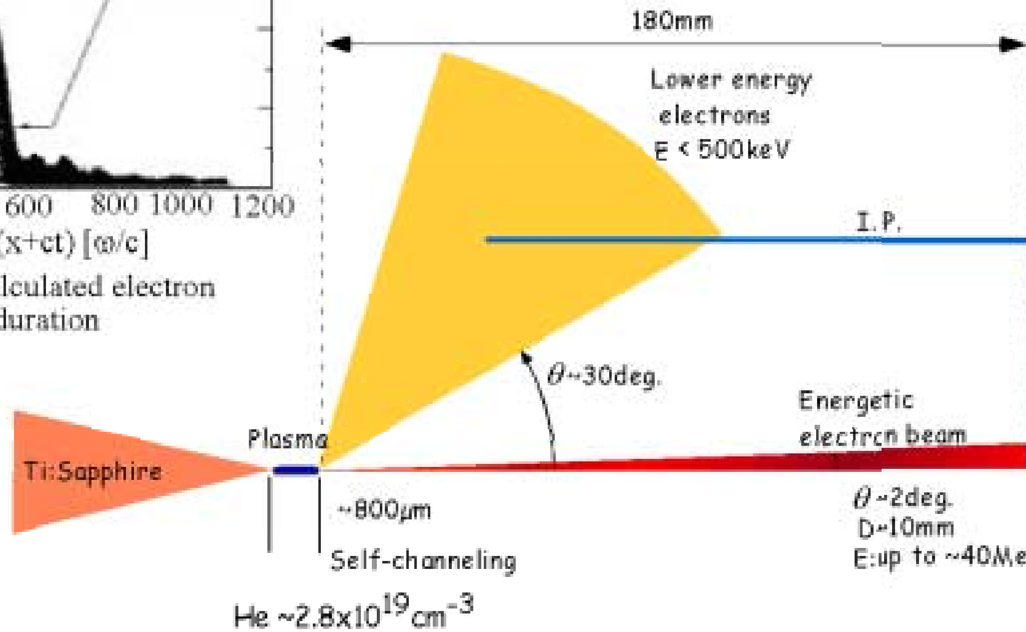
Gas density ~1.0×10^{19} cm^{-3},
Laser Intensity ~1.0×10^{19} Wcm^{-2}

Femtosecond e-Beam Generation from Gas Jet (Picture from experimental results)



The calculated electron bunch duration

Low density case



Typical parameters of electron generation

Electron	
Maximum energy E [MeV]	~40
Electron bunch duration [fs]	~40 (PIC)
Transverse geometrical emittance[πmm mrad]	0.1
Number of Electron N [pC]	100 (PIC)
Laser	
Laser Pulse duration τ [fs]	50
Peak power P [TW]	4.8
Spot radius(FWHM) r_0 [μm]	2.5
Focusing Intensity [Wcm^{-2}]	1x10^{19}
Laser strength a_0	~2.0
Others	
Gas density of He n [cm^{-3}]	2.8x10^{19}
Rayleigh Length Z_R [μm]	53
Self-Channeling L [μm]	800 (PIC)
Acceleration gradient [GeV/m]	50

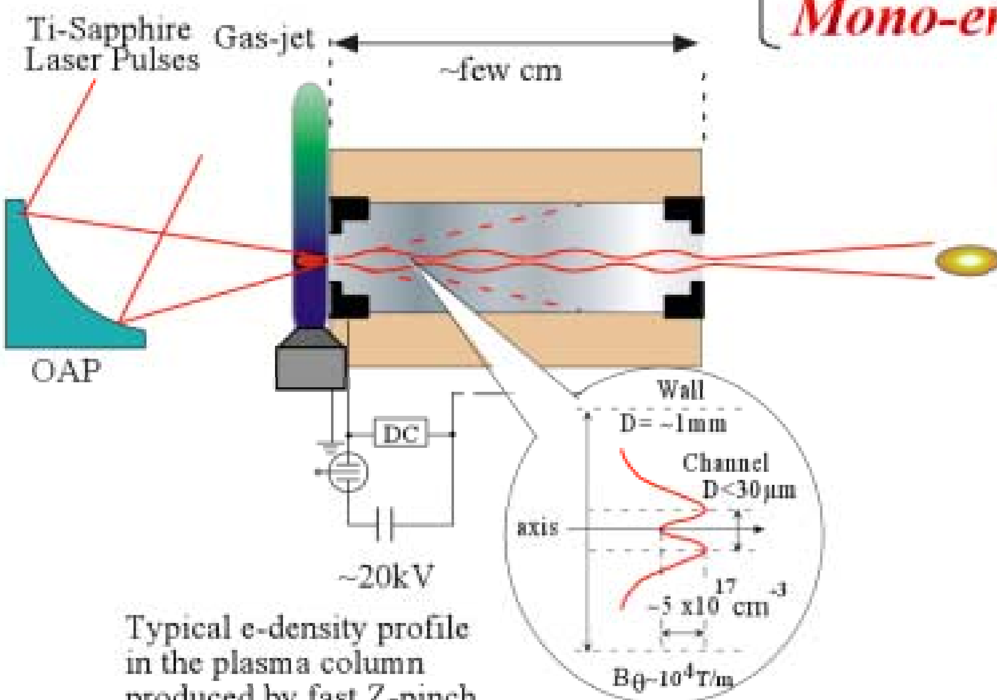
Mono-energetic spectra?

We are developing a capillary plasma target

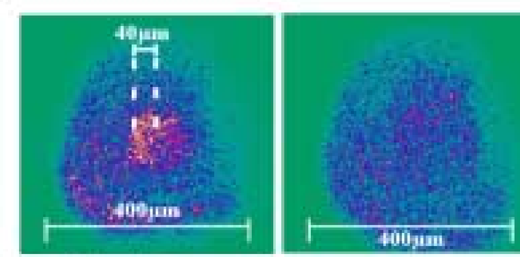
- ***High-Density Gas Jet***
- ***Controlled-prepulse***

→ ***High-charge injection*** / ***Wave breaking at the interface***

- ***Capillary Discharge(Z-pinch?)*** → ***Optical wave-guide*** / ***Further Acceleration*** / ***Mono-energetic spectrum***



Optical waveguide have been already demonstrated.

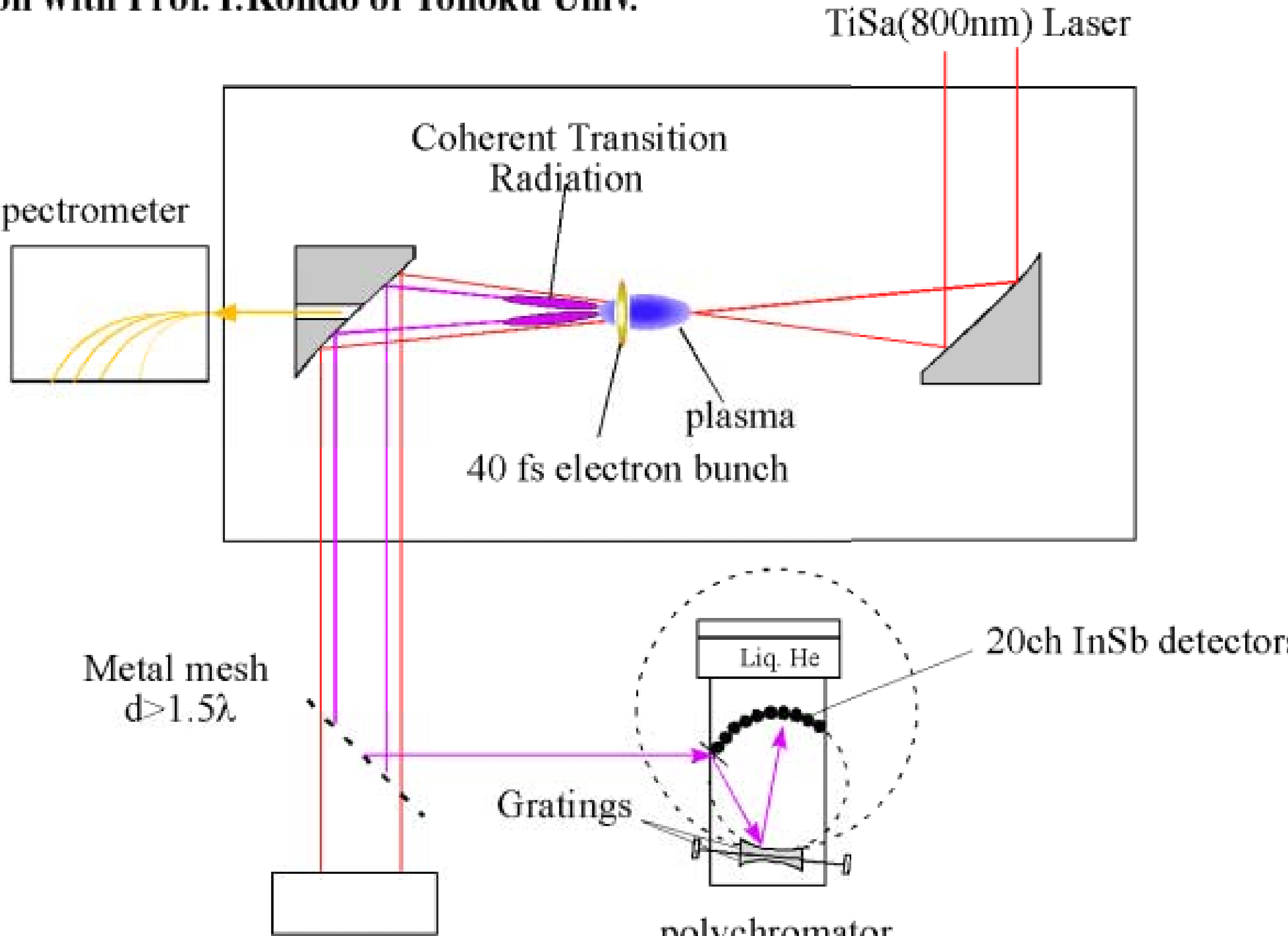


Guided Beam Without Guide

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

Measurement for Femtosecond Electron Pulse Duration in one shot

Collaboration with Prof.Y.Kondo of Tohoku Univ.



Pump-and-probe Experiment Using Plasma Cathode at University of Tokyo

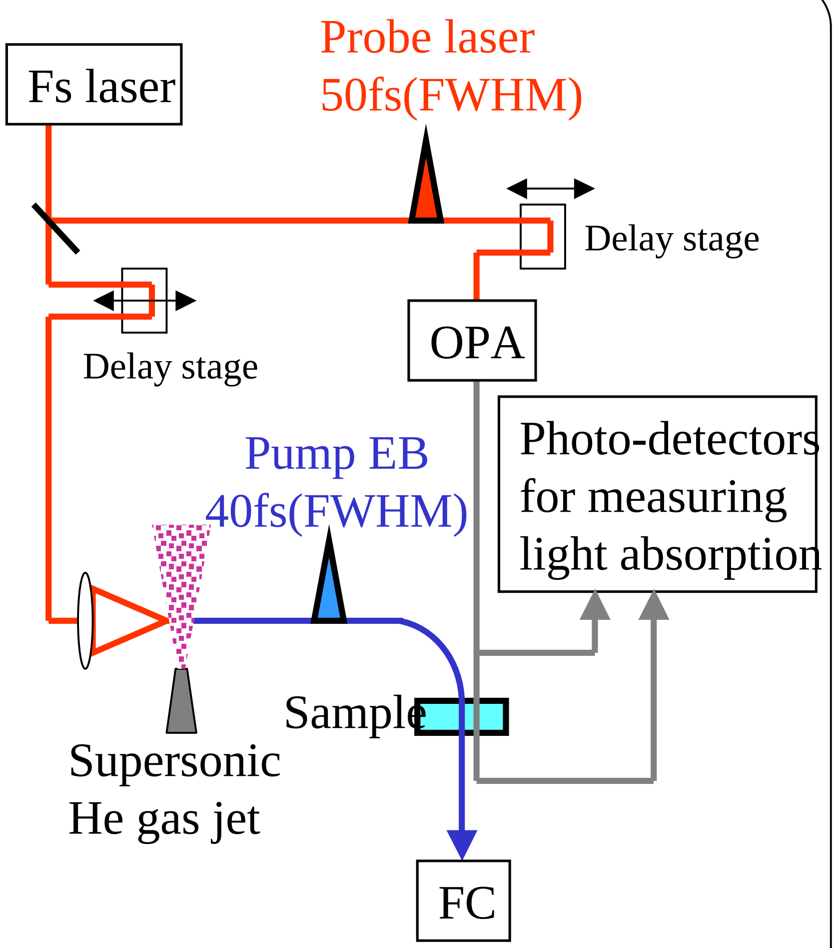


Fig. Schematic diagram of pump-probe experiment using plasma cathode

Dominant factors for time resolution

- EB for pump : 40fs(FWHM)
- Laser for probe : 50fs(FWHM)
- Timing jitter : ~0fs
- Desynchronization in sample : ~1ps/mm

Current problems to be solved

- Electron beam
  - Energy spread : 100% → <10%
  - Charge : <1nC → >2nC
  - Stability of charge : 100% → <1%

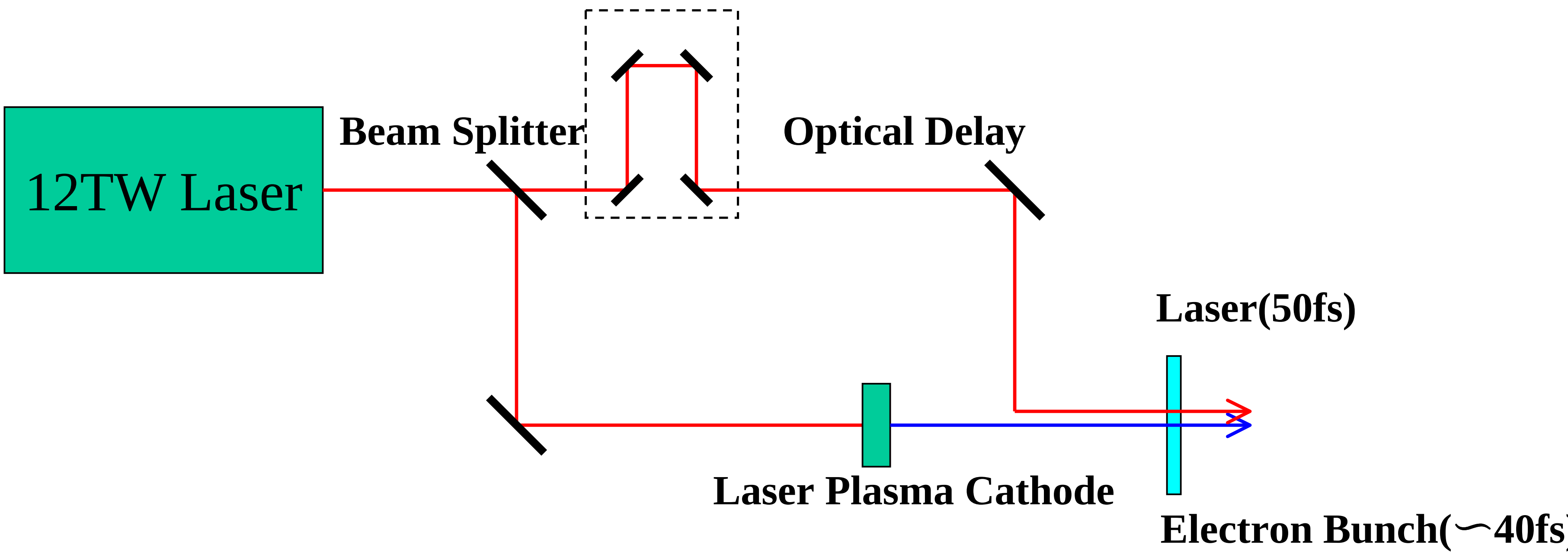
Development of the system

Subject : radiolysis of liquids

- Direct observation of radiation-induced physico-chemical processes within 1ps (Vibrational&rotational relaxation, intramolecular reactions, geminate ion recombination etc.)

Big Advantage of Laser Plasma Accelerator for Pump-and-probe analysis

- Synchronization is perfectly passive without any electronics.
- No timing jitter and drift between laser and secondary beam.
- Femtosecond time-resolved analysis is surely available after the bean quality and stability are upgraded.



Summary of Synchronization

1. Laser vs Accelerator Synchronization System via Electronics

Picoseconds time-resolution

2. Laser Seeded Staged Accelerator

Femtoseconds time-resolution

Available for multibunches

3. Laser Plasma Accelerator

Beam Splitter enables even Attoseconds time-resolution

After Stable and reliable beam generation and diagnosis are established

Summary

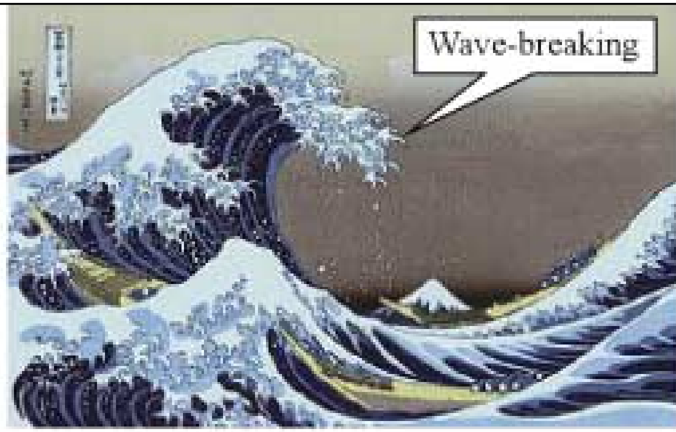
- **Laser pre-pulse effect**

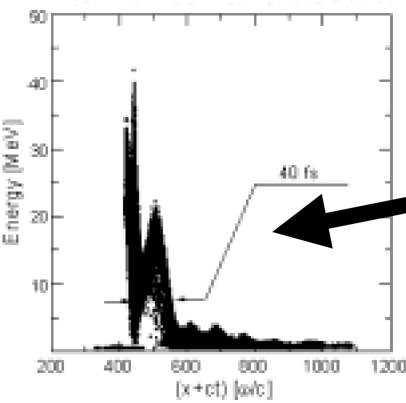
— e-beam generation depends strongly on the laser pre-pulse. —
Pre-plasma control is essential for ejection of MeV "e-beam" from gas jet.

  - **A Cavity formation by laser prepulse**
    (No pre-plasma channel for short Rayligh length system)
  - Density steepening in the cavity due to shock wave
  - Electron injection at the shock front due to wave breaking of main pulse
  - **Strong refraction of the laser pulse at the cavity in high-density plasma**
  - **PIC simulation suggest the electron bunch has ~40 fs bunch duration.**

- **We are preparing**
  - **Gas capillary discharge target.**
  - **Shockwave controlled supersonic gas jet target.**
  - **e-bunch measurement.**

Tens Femtosecond or Quasi-Monochromatic Electron Single Bunch by Laser Plasma Cathode (RAL, LBNL, LOA, AIST, U.Tokyo at AAC2004)

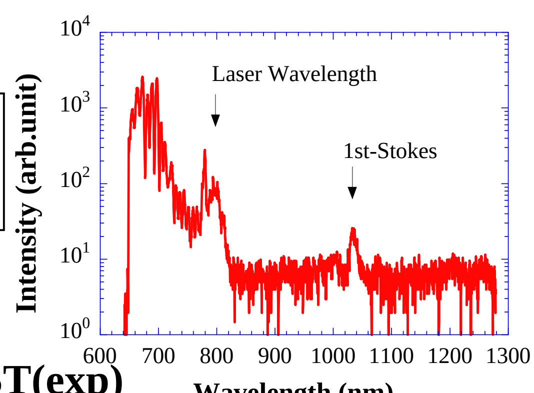




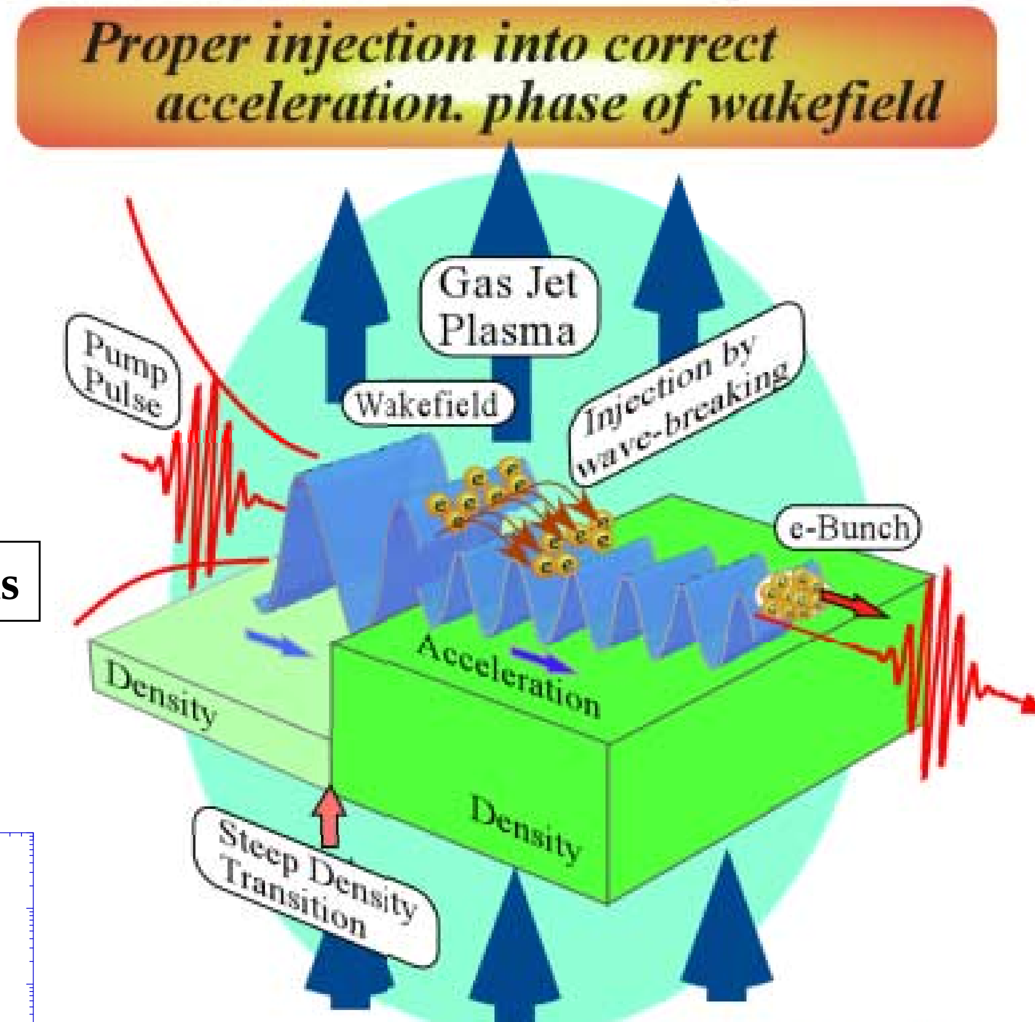
Tens femtoseconds

U.Tokyo(cal)

Quasi-monochromatic



AIST(exp)



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

AAC 2004 Experimental Results Laser-Plasma Accelerator WG

	LOA	LBNL	RAL-alphaX	AIST	University of Tokio	Neptune, UCLA	NRL	JAERI	Osaka University	KERI
Scheme	SM(for-ced)LWFA	SM-LWFA	SM-LWFA	SM-LWFA	SM-LWFA	PBWA	SM-LWFA	SM-LWFA	LWFA	SM-LWFA
Laser parrs	30TW 0.8 mkm, 3x1018 W/cm2, W0=18 mkm, 30fs	8TW 0.8 mkm,1x1019 W/cm2W0 =7 mkm, 55fs	16TW 0.8 mkm ,1x1018 W/cm2W0 =25 mkm,40fs	2TW 0.8 mkm 5x1018 W/cm2W0 =5 mkm,50fs	6TW 0.8 mkm 1x1019 W/cm2W0 =6 mkm,50fs	1TW 10.3+ 10.6.mk	10TW 1.06 mkm3x1018 W/cm2W0 =12 mkm, 500s	20TW 0.8 mkm2.x1019 W/cm2W0 =5 mkm,, 23fs	30TW 1.06 mkm	2TW 0.8 mkm
Plasm. Density	6x10^{18} cm^{-3}	2x10^{19} cm^{-3}	2x10^{19} cm^{-3}	.1.5x10^{20} cm^{-3}	1.8x10^{19} cm^{-3}	1x10^{16} cm^{-3}	1x10^{19} cm^{-3}	1.4x10^{20} cm^{-3}	6x10^{16} cm^{-3}	1x10^{18} cm^{-3}
Injector type	Self-trapped	Self-trapped	Self-trapped	Self-trapped	Self-trapped	12 MeV external	Optical Injection ioniz.	Self-trapped	Self-trapped	Self-trapped
Energy Gain	>170±15 MeV, 500 pC,	86 ±2 -150 MeV 300 pC	78 ±2 MeV 20 pC	7 ±1 MeV 2 pC	40 MeV	38 MeV	20 MeV	40 MeV	100 MeV	2 MeV
		Channel		Integrated over 90 shots spectrum		Ponderomotive channel	2 TW beam for LIPA injector		Glass capillary	