Generation of energetic electrons from a laser plasma cathode and the future applications for pulse radiolysis, Thomson scattering X-ray generation, and electron microscopy

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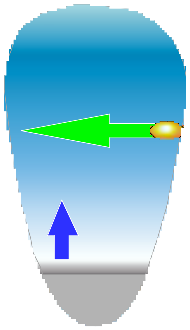
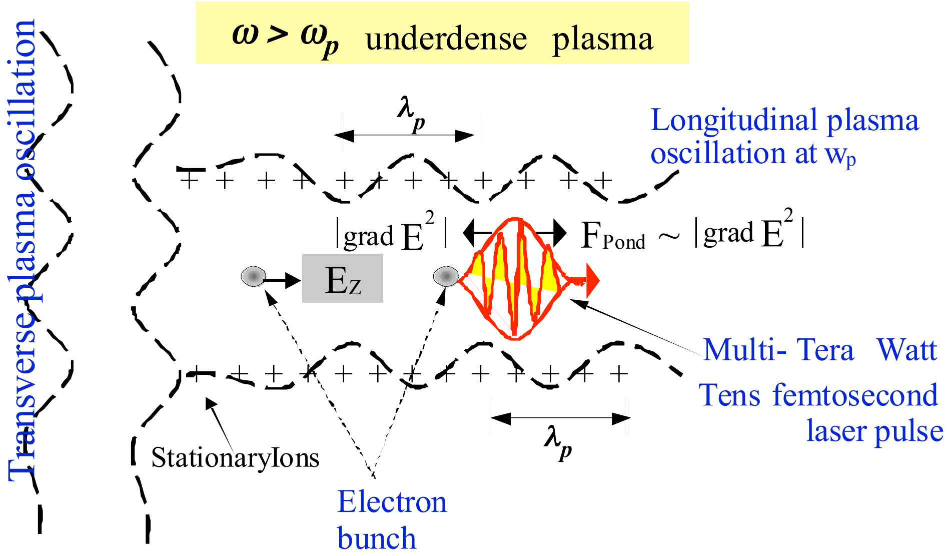
The physics and Applications of High Brightness Electron Beams, Erice (Italy), 10th-14th Oct. 2005.

What is the laser plasma cathode.

Tera-watt laser + plasma + wave breaking → energetic electrons





$\omega > \omega_p$ underdense plasma

λ_p

Longitudinal plasma oscillation at w_p

$|\text{grad } E^2|$

$F_{Pond} \sim |\text{grad } E^2|$

E_Z

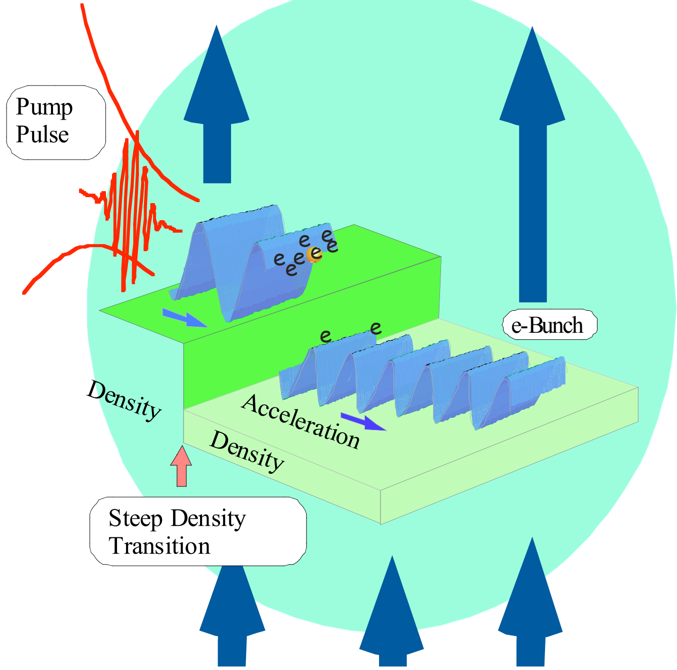
Multi- Tera Watt Tens femtosecond laser pulse

λ_p

Transverse plasma oscillation

StationaryIons

Electron bunch



Pump Pulse

e-Bunch

Density

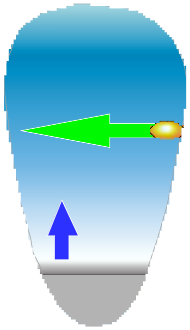
Acceleration

Density

Steep Density Transition

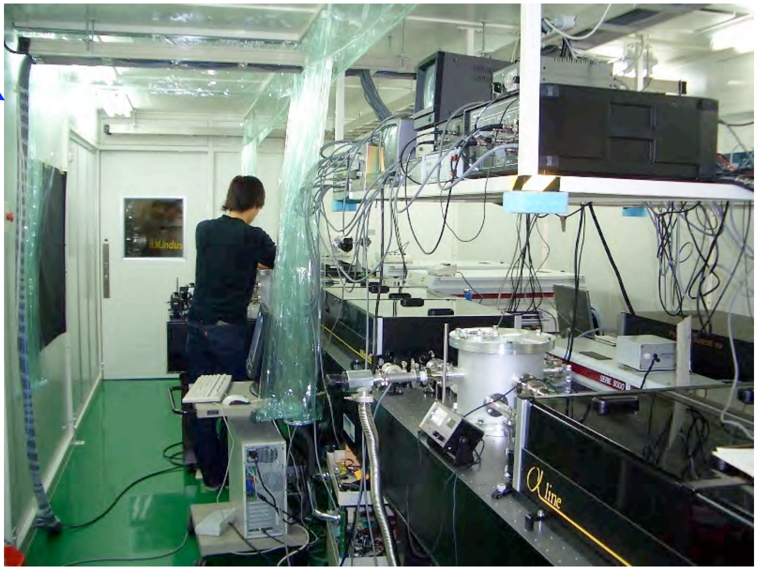
Characteristics of the laser plasma cathode

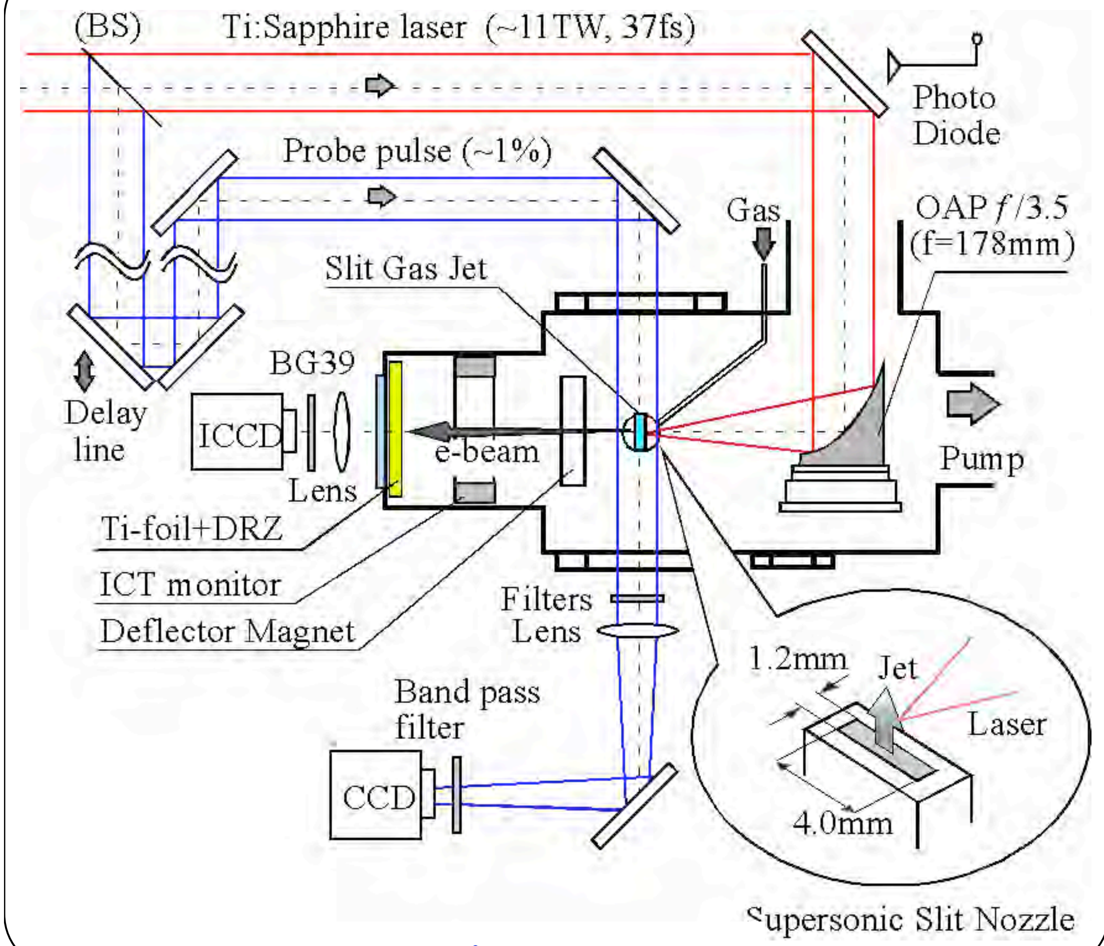
- **Femtosecond electron bunch < 100 fs**
  - **-- Ultrashort laser pulse + high frequency of the plasma wave**
- **High accelerating gradient ~ 100 GV/m**
- **Moderate energy ~ 10s MeV within 1 mm acceleration length**
- **Jitter free**
  - **-- Multiple pulses divided from a single laser pulse**
- **Good emittance ~ 1 πmmmrad**
  - **-- Small laser spot and rapid acceleration**



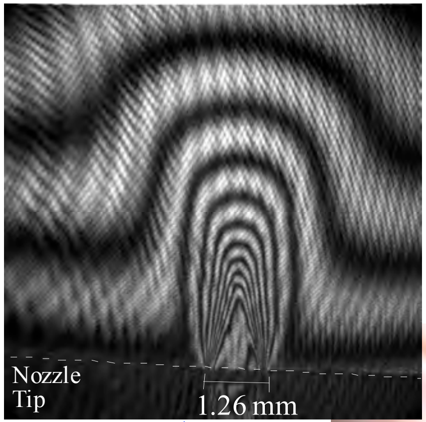
Apparatus for laser plasma cathode

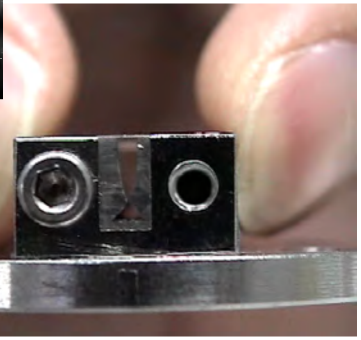
Tera watt laser system





Experimental setup

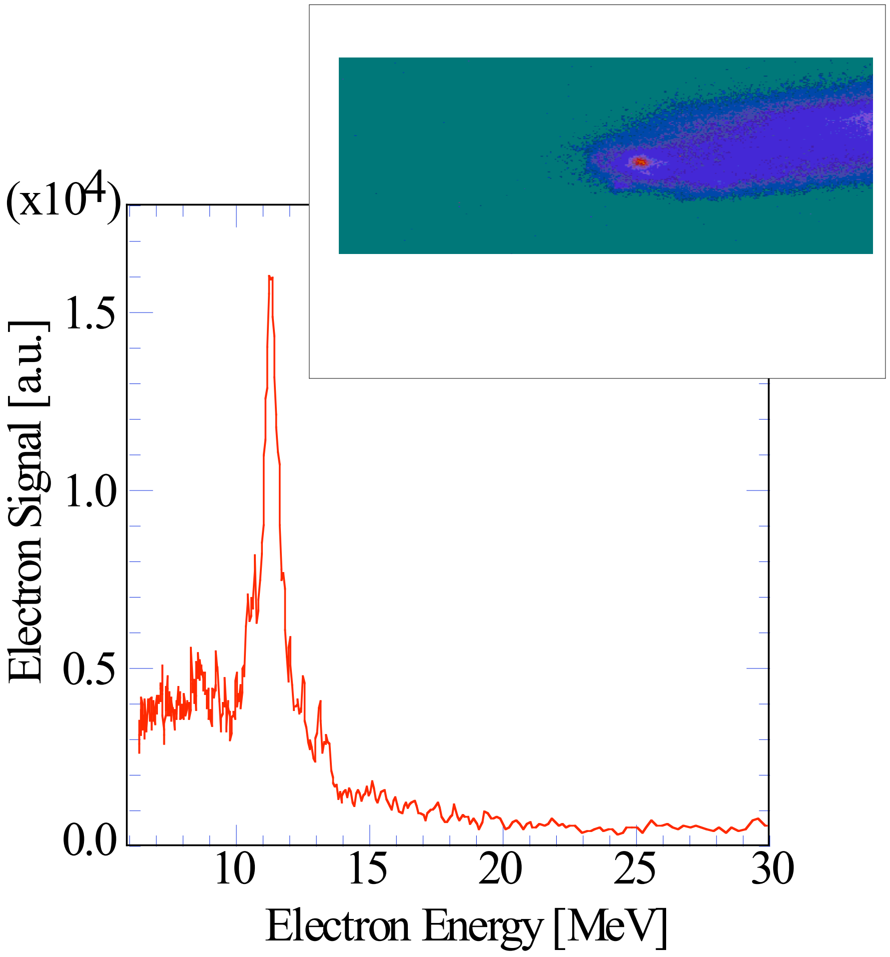




Gas jet

Mono energetic electron beam from laser plasma cathode

Qasi mono energetic electron spectrum



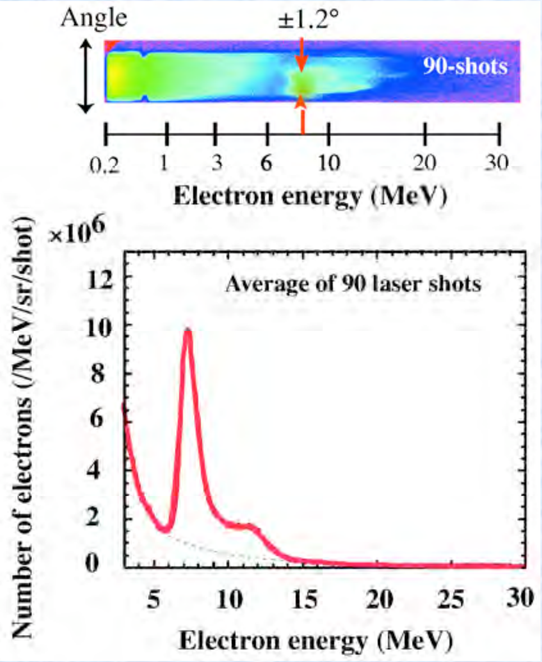
Laser Parameters

- 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)
  ~2.2×10^{19}Wcm^{-2}
  a_0~3.1
- Contrast Ratio 1:5×10^{-7}
- Power Density
  for Pre-pulse
  2ns~1.0×10^{13}Wcm^{-2}
  few ps~1.0×10^{16}Wcm^{-2}

Mono-energetic Electron Beams

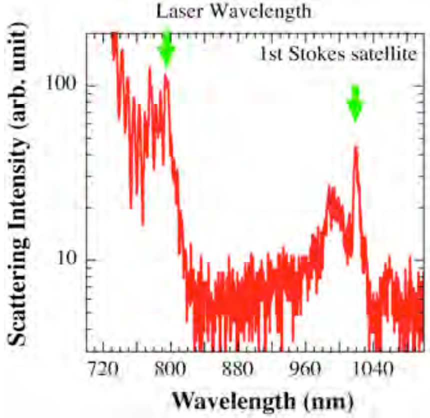
Mono-energetic electron beams were accelerated by laser-plasma particle accelerators in 2004.

- **Energy gains and electric charges were 7-15 MeV and 2- 3fC, respectively.**
- **The normalized emittance was approximately 0.7 π mm mrad.**



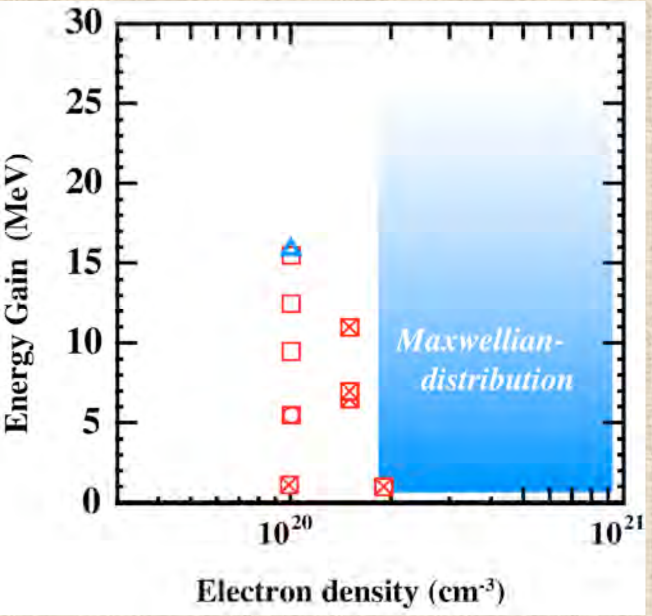
Electron Energy Spectrum

Forward scattering Spectrum



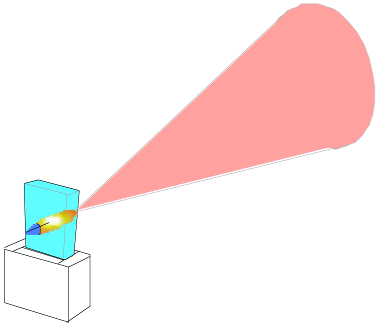
The Stokes satellite peak clearly shows the self-modulated laser wakefield.

Energy Gain vs. Electron D



Mono-energetic beam acceleration is limited in an narrow density range for a fixed laser power ($n_e \approx 1 \sim 1.5 \times 10^{20} cm^{-3}$, P_L= 2TW).

2-staged acceleration for more improved electron beam



	Low density (~10^{17}cm^{-3})	High density (~$10^{19\text{-}20}$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	???

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.

Applications of laser plasma cathode

Through laser plasma cathode we will have;
femtosecond electron beams from a compact accelerator,
jitter-free system synchronized with a femtosecond laser pulse.

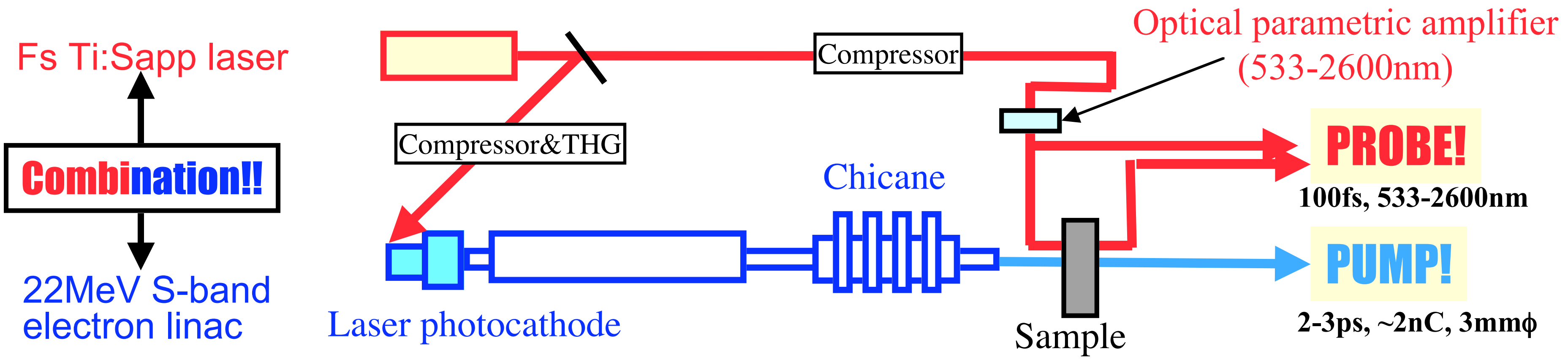
↓

Various applications such as,

- Femtosecond pulse radiolysis for radiation chemistry
- Femtosecond X-ray generation through laser Thomson scattering
- Time-resolved electron microscope

Pulse radiolysis with a conventional LINAC

Ultra-fast pump-and-probe pulse radiolysis study : radiation induced fast processes



Fs Ti:Sapp laser

Combination!!

22MeV S-band
electron linac

Compressor&THG

Compressor

Optical parametric amplifier
(533-2600nm)

Chicane

Laser photocathode

Sample

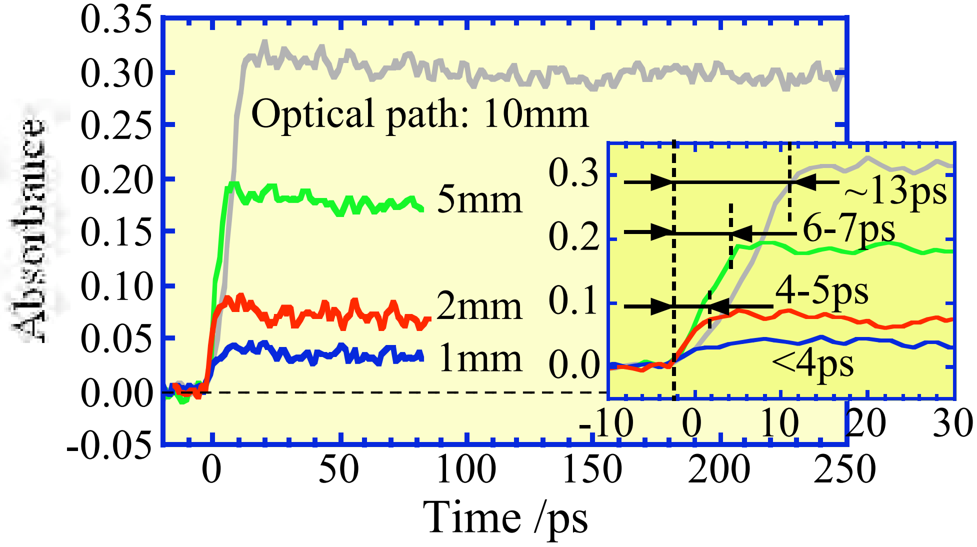
PROBE!

100fs, 533-2600nm

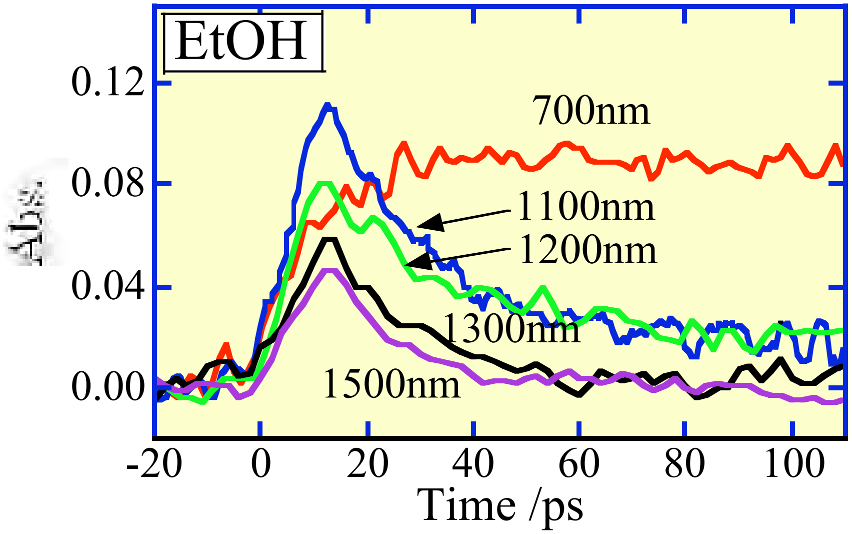
PUMP!

2-3ps, ~2nC, 3mmϕ

Time behaviors of hydrated electrons in water:
Solvation time < time resolution < 10ps



Time behaviors of solvated electrons in ethanol:
Observation of solvation process (e^-_{pre} ? ¨ e^-_{sol})

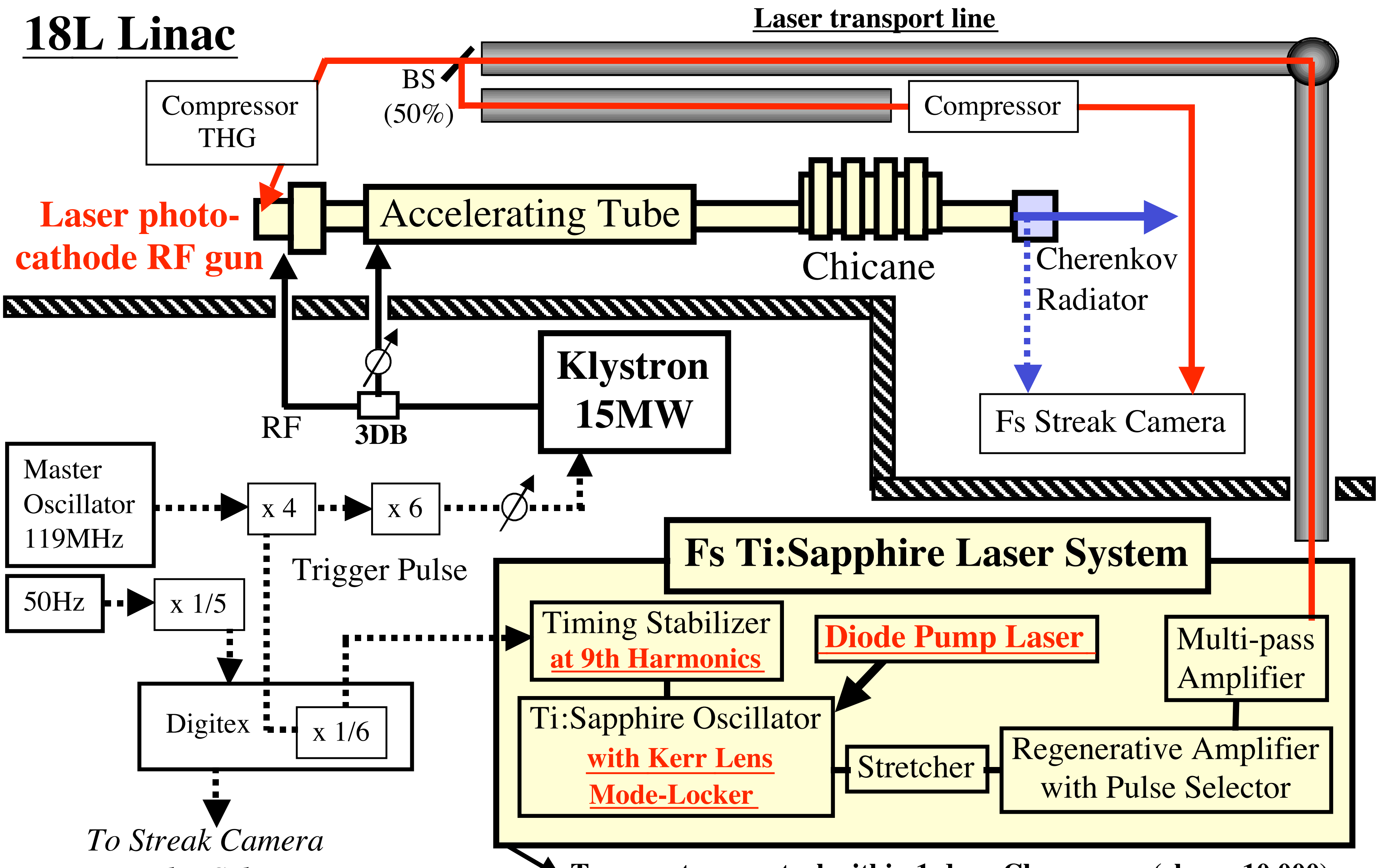


Synchronization of laser and LINAC

Precise Synchronization System at UTNS

Beam-Material Interactions
www.utns.jp/~beam

18L Linac



Laser transport line

BS
(50%)

Compressor
THG

Compressor

Laser photo-cathode RF gun

Accelerating Tube

Chicane

Cherenkov
Radiator

Fs Streak Camera

RF

3DB

Klystron
15MW

Master
Oscillator
119MHz

x 4

x 6

Trigger Pulse

50Hz

x 1/5

Digitex

x 1/6

To Streak Camera
To Pulse Selector

Fs Ti:Sapphire Laser System

Timing Stabilizer
at 9th Harmonics

Diode Pump Laser

Multi-pass
Amplifier

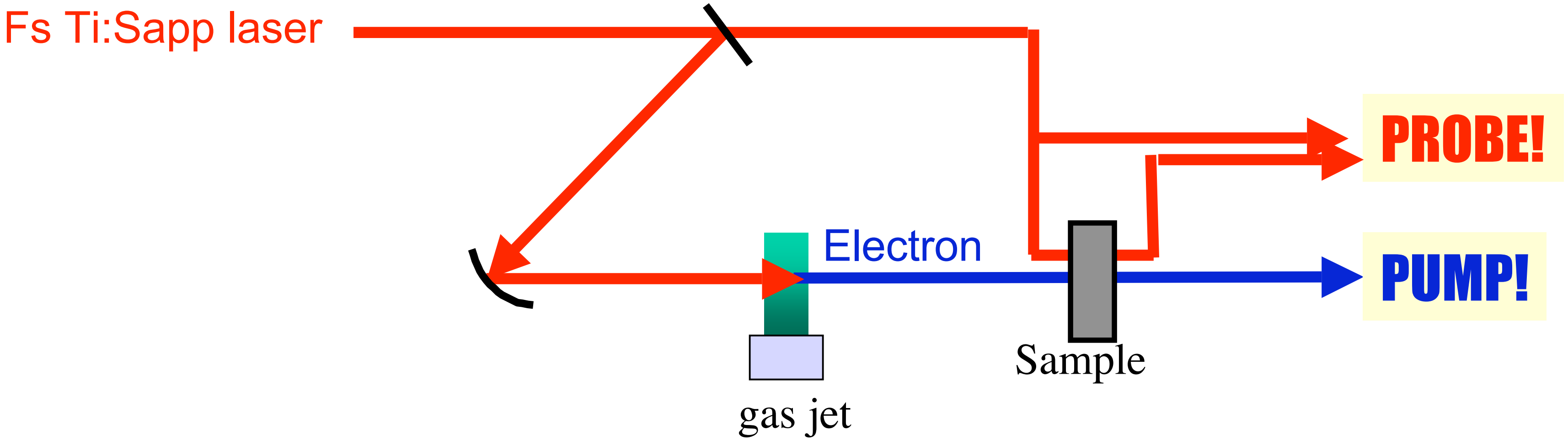
Ti:Sapphire Oscillator
with Kerr Lens
Mode-Locker

Stretcher

Regenerative Amplifier
with Pulse Selector

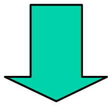
Temperature control within 1 deg, Clean room (class : 10,000)

Pulse radiolysis with laser plasma cathode



A laser pulse divided into electron generation pulse and probe pulse

- Jitter-free
- Femtosecond pulses



Femtosecond resolution!

Very simple setup!

Laser Thomson scattering with laser plasma cathode

Hard X-rays (~10-20 keV) in a 1-2° cone can be produced with 12TW Laser

Normalized Intensity

Normalized Intensity

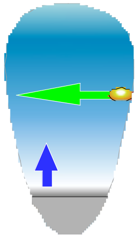
Laser pulse and electron
bunch encounter can be
produced with use of
the laser self-focusing

F.He, Y.Lau, D. Umstadter, R.Kowalczyk
PRL, 90,055002 (2003)

$$\omega \sim m\omega_0 8\gamma_0^2/(1+a_0^2)$$

Laser Thomson scattering with laser plasma cathode

Moving through the laser pulse, a relativistic electron transforms the laser light to X-rays. The total number of photons produced by the electron is



Number of photons scattered by single electron:

$$n = \sigma W / h\omega$$

$n \sim 0.3$

$\sigma \sim \pi r_e^2 = \pi e^4/(m_e c^2)^2$

σ : cross-section

W : laser energy density

→ $2\text{x}10^6$ photons are scattered
10pC electron single bunch.

→ $2\text{x}10^7$ photons/sec @10Hz

If we can avoid the diffraction effects due to pre-plasma,

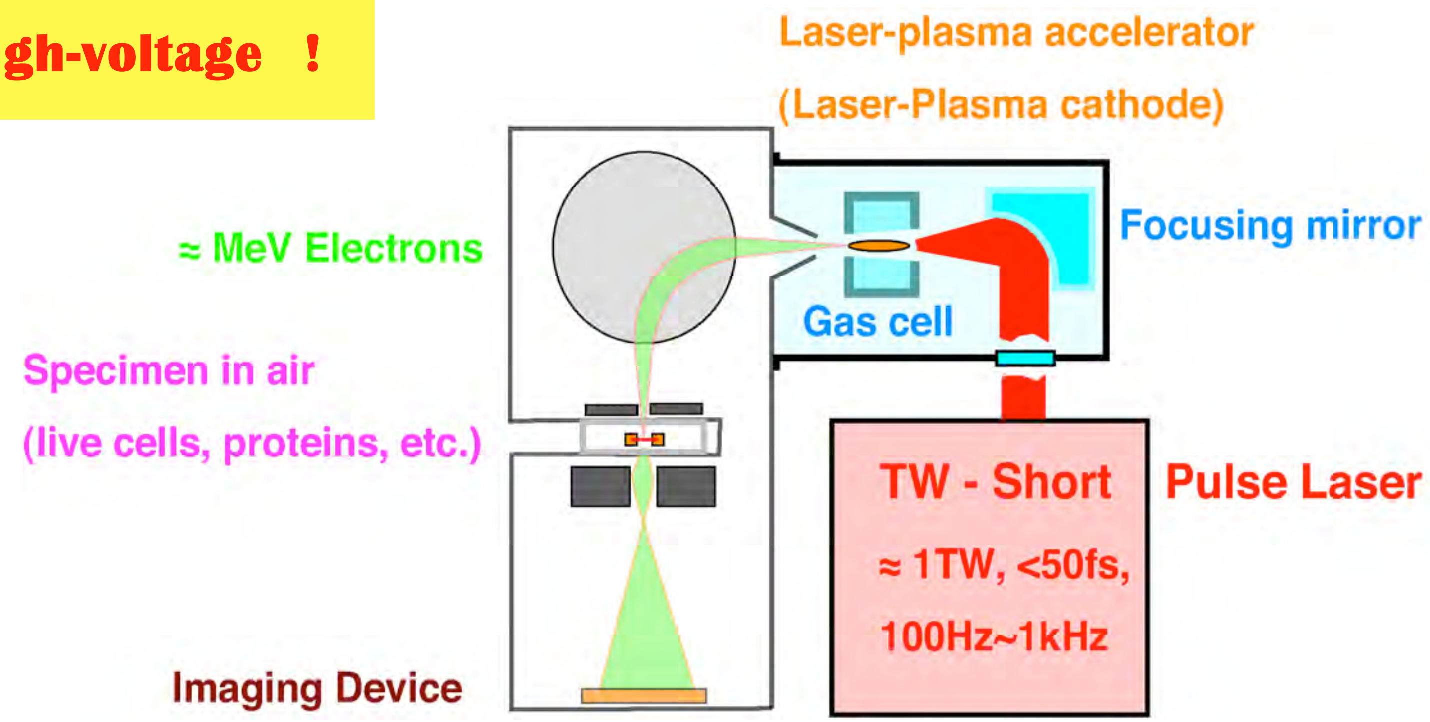
→ 100pC / bunch → $2\text{x}10^8$ photons/sec @10Hz

Present parameters
in experiment

- Wavelength ~800nm
  Pulse duration ~40fs
  Laser energy 600mJ/pulse
  (300mJ for drive pulse,
  300mJ for colliding pulse)
  Spot size ~10µm in D

A Strawman Design of Laser-driven Microscope

No high-voltage !



- **Ultra-short pulse of ≈10fs might be possible to accelerate electrons in the atmospheric pressure.**
- **Laser-plasma cathode technique will enable us to observe live specimen by the electron microscope.**
- **Pump-probe technique with fs-resolution will be possible.**

Summary

Laser plasma cathode is a high quality electron source.

- Femtosecond electron bunch
- Jitter-free synchronization with a femtosecond laser pulse
- Compact

We will apply laser plasma cathode to femtosecond applications.

- Femtosecond pulse radiolysis
- Femtosecond X-ray generation via laser Thomson scattering
- Time-resolved electron microscope