Design and construction of ultrafast pulse radiolysis system using laser photocathode rf-gun combined with fs laser

Jun. 26th, 2004
Brookhaven National Laboratory, USA

Yusa Muroya, Mingzhang Lin, Hokuto Iijima, Toru Ueda, Mitsuru Uesaka, Yosuke Katsumura

Nuclear Engineering Research Laboratory
University of Tokyo, JAPAN
Development of new pulse radiolysis system

- Time resolution: ~50ps → ≤10ps
- Stroboscopic method (pump-and-probe)
  - Laser photocathode rf-gun and/or fs laser
  - Projects in progress in the world
    BNL, Pari-sud, Waseda Univ., Sumitomo Heavy Industries, Osaka Univ., ANL etc.

Dynamics

Absorption

Optical delay

\[ t < 0 \quad t = 0 \quad t > 0 \]
Precise Synchronization System at NERL

18L Linac

Compressor THG

Laser photocathode RF gun

Accelerating Tube

RF

3DB

Klystron 15MW

Master Oscillator
119MHz

50Hz

x 4

x 1/5

Digitex

x 1/6

To Streak Camera
To Pulse Selector

Diode Pump Laser

Timing Stabilizer at 9th Harmonics

Diode Pump Laser

Regenerative Amplifier with Pulse Selector

Multi-pass Amplifier

Stretcher

Temperature control within 1 deg. Clean room (class : 10,000)
Transport line for femtosecond laser

18MeV linac
Wave guide
(7.5MW, 10Hz S-band RF)

Beam
(4-5MeV, 3nC, ~20πmmrad
dark current : ~8nA)

Photocathode RF-Gun
• Photoelectron cooler than thermionic emission
• Acceleration up to 4MeV by gradient of 100MV/m

Laser
(265nm, ~100 µJ, 4-6ps,
D=3mm at cathode, 10Hz)

2 getter, 2 ion pumps (140dm³): <10⁻¹⁰ Torr
RF-gun study

- QE: \( \sim 1.2 \times 10^{-4} \)
- Emittance: \( 20\pi \) (hor.) and \( 20\pi \) (vert.) mmmrad
- >3nC/pulse@90deg

Adopted for pulse radiolysis
**Generation of ultra-short electron beam**

**Charge transportation**
- Laser (265nm): \(~100\mu\text{J}\)
- Gun phase: \(~120\text{deg}\)
- ACC phase: \(~80\text{deg}\)
- 80~90% transmission (Oct. 2003)

**Optimized electron beam**

<table>
<thead>
<tr>
<th>Sections in linac</th>
<th>Photocathode</th>
<th>ACC</th>
<th>Chicane</th>
<th>Linac end (no slit)</th>
<th>Linac end (3mm slit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge /nC</td>
<td>2.5</td>
<td>2.5</td>
<td>2.4</td>
<td>2.3</td>
<td>1.7-2.0 nC</td>
</tr>
<tr>
<td>Dark current /nC</td>
<td>(~0.8)</td>
<td>(~0.2)</td>
<td>(~0.05)</td>
<td>(~0.05)</td>
<td>(~0.05) nC</td>
</tr>
<tr>
<td>Pulse width /ps</td>
<td>7</td>
<td></td>
<td>&lt;1</td>
<td></td>
<td>2ps (FWHM)</td>
</tr>
<tr>
<td>Energy /MeV</td>
<td>4-5</td>
<td></td>
<td></td>
<td></td>
<td>(22\pm0.1\text{MeV})</td>
</tr>
</tbody>
</table>

\[ \rightarrow >40\text{Gy/pulse is available} \]
2 factors affecting timing jitter

$\sigma_1$ : Timing stabilization in laser oscillator - 100fs by passive mode-lock

$\sigma_2$ : Fluctuation of RF power & phase
**Stable acceleration(1) : stable RF**

- Fluctuation of RF power/phase
- Fluctuation of energy
- Fluctuation of arrival time

- 7ps (FWHM)
- 2-3nC

**Stable acceleration(2) : mutual jitter**

- Independently supplied RF : mutual jitter
- ~ps

- No mutual jitter
- <ps

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**Dipole magnets**

- Trajectory of the beam
- 2ps (FWHM)
- 2-3nC

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**RF-gun**

- Accelerating tube
- 7MW KLY

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**RF-gun**

- Accelerating tube
- 7MW KLY

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**RF-gun**

- Accelerating tube
- 15MW KLY

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**RF-gun**

- Accelerating tube
- No mutual jitter
- <ps
Synchronization of electron beam and laser by FESCA

- Xe chamber used for Cherenkov radiator

Synchronization experiment

- Timing jitter during minutes: <500fs(rms)
  - Stabilized RFs, passive mode-lock
  - Simulation by PARMERA: 330fs(rms)
- Large drift
  1. Cooling system in ACC: $\Delta T < 0.01K$
  2. Temp. control in rooms: $\Delta T < 0.5K$
  3. N$_2$ purge in 50m transport line
- Pulse radiolysis: 40~60min./data $\rightarrow$ <1ps(rms)
The laser transport line is 50 m long, and 14 bellows are used.

(iii) The mirror chamber with flexibility due to the bellows is moved by the pressure.

(ii) The pressure difference between inside and outside of the transport line chamber applies the force to the mirror chamber.

• In the chambers… Vacuum  ➞ Atmospheric pressure N\textsubscript{2} gas.  

*To suppress the pressure effect!*
**Improvement: problems solved**

**Time resolution vs. dose**

1. 2~3ps: pulse width (EB)
2. 100fs: pulse width (laser)
3. <1ps: synch.
4. 5ps /5mm: $\Delta t$ passing through $H_2O$

→ Thinner cell & focused EB

Note: $O.D. = \varepsilon C l$

$l\downarrow$ for better time resolution, but $O.D.\downarrow$

then, $C\uparrow$ for $O.D.\rightarrow$

**Introduction of white light continuum**

- 795nm → white
- Worse stability of intensity
- $S/N\downarrow$ then average $\uparrow$

<table>
<thead>
<tr>
<th></th>
<th>Previous</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>Fundamental</td>
<td>White</td>
</tr>
<tr>
<td></td>
<td>795nm</td>
<td>400-1100nm</td>
</tr>
<tr>
<td>Average</td>
<td>16</td>
<td>64</td>
</tr>
<tr>
<td>Noise</td>
<td>~0.005 OD</td>
<td>~0.015 OD</td>
</tr>
</tbody>
</table>

**Improvement**

<table>
<thead>
<tr>
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<th>Current</th>
</tr>
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<tbody>
<tr>
<td>Charge</td>
<td>0.8-1.0nC</td>
<td>1.7-2.0nC</td>
</tr>
<tr>
<td>Beam size</td>
<td>4mm</td>
<td>3mm</td>
</tr>
<tr>
<td>Dose</td>
<td>13-15Gy</td>
<td>&gt;40Gy/pulse</td>
</tr>
<tr>
<td>Pulse width</td>
<td>3ps</td>
<td>2ps</td>
</tr>
</tbody>
</table>

Dose increase & Wide measurement wavelength
Radiolysis of water measured at 700nm

- Time behaviors of $e_{aq}$ at 700nm

**Results**

<table>
<thead>
<tr>
<th>$l$ /mm</th>
<th>10</th>
<th>5</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>O.D.</td>
<td>0.32</td>
<td>0.19</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>S/N</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Dose</td>
<td>40Gy</td>
<td>47Gy</td>
<td>50Gy</td>
<td>50Gy</td>
</tr>
<tr>
<td>Time resol. /ps</td>
<td>12-13ps</td>
<td>6-7ps</td>
<td>4-5ps</td>
<td>&lt;4ps</td>
</tr>
</tbody>
</table>

**Time resolution:**

$$\delta_{\text{total}} = \delta_{\text{diff}} + (\delta_{E}^2 + \delta_{L}^2 + \delta_{\text{sync}}^2)^{1/2}$$

Dominant factor: $\delta_{\text{diff}}$
due to refractive index $n=1.33$

**Optical path:**

- 10 mm
- 5 mm
- 2 mm
- 1 mm

**Beam-Material Interactions**

www.utnl.jp/~beam
A new pulse radiolysis system combined with laser photocathode rf-gun and fs white light continuum has been developed.

Some problems have been pointed out. Consequently, most of those were improved.

<4ps time resolution has been attained.

Future works
  Introduction of OPA for extending measurement wavelength