Development of Photocathode RFgun at SPring-8

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1. Introduction

- 1.1 Direction of the Research
- 1.2 History
- 1.3 Characteristics of SPring-8 RF gun
1.1 Direction of the Research

• Lowest Emittance Beam Generation based on
  
  – 3D Laser Shaping with long-term stability
  – 3D Beam Dynamics Simulation
  – Cavity Technology for Higher RF Field
  – New Cathode Developments
  – High Resolution Emittance Monitor
1.2 History

1996  Study of photocathode RF guns started for the next generation photon source
1999  First beam test
       A new laser system ordered
2001  New Ti:Sapphire laser system installed
2002  Emittance $2 \, \pi \text{mm mrad}$ with homogenizing
       Cartridge type cathode development started
2003  New gun & laser test room constructed and an accelerating structure installed
2004  Maximum field of $190 \, \text{MV/m}$ at cathode
       Laser was stabilized with $0.2\%$ for 1 Month
2005  3D-laser shaping system was completed
       Emittance $1.7 \, \pi \text{mm mrad}$ with Flattop (DM)
1.3 Test Facility

RFgun1 + 3m accelerating structure -----> Low emittance beam production
RFgun2 -----> cathode study, rf breakdown study, surface physics
1.4 Characteristics of SPring-8 RFgun

1. Laser
   • THG of Ti:Sa Laser (263 nm, 10Hz, 850 μJ/pulse)
   • Energy stability (passive) : 0.7% rms @THG(263 nm)
   • Spatial profile control : Homogenizer (or Deformable Mirror)
   • Temporal distribution : Stretched with SiO₂ rods (or SLM)
   • 3D-Ellipsoidal : Fiber Bundle with Deformable Mirror

2. RF cavity
   • S-band (2856MHz), Single-cell pill-box type
   • Cathode : cavity wall ( RF cavity1)
     cathode plug in a vacuum cartridge (RF cavity2)
   • High electric field on cathode : 190 MV/m (RF cavity1)

3. Synchronization of Laser & RF
   • RF generation(2856 MHz) from laser pulses(89.25 MHz)
   • RMS jitter (@low level) < 100 fs
2. Laser

- 2.1 Laser System Configuration
- 2.2 Laser & RF Synchronization
- 2.3 Laser Profile Control
- 2.4 Long-term Stability of Laser
2.1 Laser System Configuration

- **Mode-locked Ti:Sapphire oscillator**
- **Stretcher**
- **Regeneration amplifier**
- **Multipass amplifier**
- **Compressor**
- **THG + Stretcher**

- **Diode-pumped Frequency-doubled Nd:YVO4 Laser**: 532 nm, 5W (CW)
- **Q-Switched Frequency-doubled Nd:YAG Laser**: 532 nm, 140 mJ
- **40 mJ**
- **532 nm**
- **790 nm**
- **20 mJ, 40 fs**
- **790 nm, 2 mJ, 300 ps**
- **790 nm, 30 mJ, 300 ps**
- **790 nm, 20 mJ, 60 fs - 22 ps**
- **790 nm, 20 mJ, 20 fs**
- **790 nm, 4 nJ, 20 fs**
- **790 nm, 300 ps**
2.2 Laser & RF Synchronization

Laser Oscillator
89.25 MHz

Laser Pulses

89.25 MHz

Pulse Train

Laser Pulses

RF signal 2856 MHz

YAG LASER

1/8.925 M Frequency Divider

89.25 MHz

Pulse Train

Piezo Driver

Slow (~8Hz) Feedback

Fast photo-diode

RF Modulation AMP

Phase Shifter

RF AMP

GPIB

PC

Frequency Counter

GPIB

Modulator

Klystron

Gun

10 Hz pulse

10 Hz pulse

To Laser Amplifier

x32

2856 MHz Bandpass Filter

Pulse signal 89.25 MHz
## Comparison of synchronization techniques

<table>
<thead>
<tr>
<th>Laser generation with master RF using PLL</th>
<th>RF generation from Laser pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronization is limited by the motion speed of piezo device.</td>
<td>Synchronization is <strong>not</strong> limited by the motion speed of piezo device.</td>
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</table>

Combination of both techniques will be planned for further lower jitter.
Short Time Jitter Measurement

Time delay between RF signal & Laser pulse measured with Tektronix TDS8200 Sampling Oscilloscope
2-3. Optimization of laser profiles

~ Spatial & Temporal ~

Beam Quality Control by

Spatial Shaping
- Microlens Array
- Deformable Mirror

Pulse (Temporal) Shaping
- SLM (Spatial Light Modulator)

Wave Front Control
- Deformable Mirror

3D-laser pulse shaping (ellipsoidal)
- Fiber Bundle (Er: Fiber Bundle Laser)
2.3.1 Physical background of ideal laser profile

$$\sigma = \sqrt{\sigma_{SC}^2 + \sigma_{RF}^2 + \sigma_{Th}^2}$$

Space charge effect consists of:

1. Linear term in radial direction
   ......possible to compensate with Solenoid Coils

2. Non-linear term in radial direction
   ......possible to suppress non-linear effects with optimization of ideal Laser Profile

Note that, in real case ideal 3D-shape can be different!
2.3.2 Spatial shaping with microlens array

**Homogenizer**

- Single (pitch: 250μm)
  - Intensity Uniformity = 10~15%
- Double (pitch: 500μm)
  - Intensity Uniformity < 5%

Structure of Microlens Array and the function
2.3.3 Measurement of Laser Pulse Profile

**Spatial:**

**UV-Laser Profile**
- Laser energy: 20 μJ
- Diameter of Laser Spot: 1.2 mm
- Charge of Electron Beam: 0.2 nC
- Emittance: 3.3 π mm mrad

**Homogenized UV-Laser Profile**
- Laser energy: 20 μJ
- Diameter of Laser Spot: 1.7 mm
- Charge of Electron Beam: 0.2 nC
- Emittance: 2.3 π mm mrad

**Homogenizing**

**Temporal:**

- Spot size: 2.0 mm
- Pulse width: 5 ps
(45-cm Fused Silica x 2)
2.3.4 THG Pulse Silica-rod Stretcher
- utilizing the dispersion in Silica -

Possible: Pulse Duration
Impossible: Square Pulse

~ 90 % pulse energy will be loss ~
2.3.5 Pulse stretching effect in Silica rods

![Graph showing the relationship between UV-laser pulse fluence and stretched pulse duration and UV-laser loss.](image)
2.3.6 Automatic laser-beam control system

- Computer-aided SLM (Spatial Light Modulator)
  - Rectangular Pulse shaping (+SA)
- Computer-aided DM (Deformable mirror)
  - Flattop spatial profile (+GA)

Additional function
- Pointing control (DM)
- Pulse energy (SLM)
2.3.7 Pulse shape control with SLM

Short laser pulse

Grating

breaks a light pulse into a spectrum
(Transform time distribution to spatial distribution)

SLM

modulates phase distribution in spectrum

Grating

transforms the spectrum into a light pulse

Utilizing silica plate modulator

• Directly shaping for UV-Laser
• Higher Laser power threshold
< 100 mJ/cm²
2.3.8 Results of Pulse shaping with SLM

- First test for computer-aided SLM was done in IR
  - **Rectangular Pulse** (width range: 2-12 ps) (rising-time: 800fs)
- Computer-aided SLM in UV
  - **Size will be bigger (~5 times)**

**Incident Pulse: Fourier Transform Limit**

**Calculate Phase Spectra!**

- **width**: 2 ps
- **rising-time**: 800 fs
FHG(197nm), THG(263nm), SHG(395nm)- System

Squared UV- Laser Pulse is generated after shaping with SLM

At present, optical transport is under construction
2.3.9 Spatial shaping with Deformable Mirror

Mirror cell: 59
Deformation step: 250

⇒ Combination: $250^{59} \sim 10^{141}$!

Al-Algorism for spatial shaping is under development

DM
Double reflection
Structure of DM-Actuator:

Voltage: \(0 \sim 255\) V

Actuator:

Initial State (All: 0V)

All: 125V

Random Voltage

All: 255V (Max. Voltage)

http://www.okotech.com/
2.3.10 Basic Concept of genetic algorithms

Genetic Algorithm

<Basic Process>

1) **Coding**: Digitize control parameters
   
   ![Gene Representation]

2) **Initialization**: prepare a set of gene

3) Basic Process
   
   Initial gene → Selection → Crossover → Mutation → Change gene sets → Evaluation

- Selection
- Crossover
- Mutation
- Change gene sets
- Evaluation
Procedure (1 step)

(1) Random select Parents and generate Children (Family)
Parents (Selected randomly from G) Create 2 Children from the Parents

(2) Drive Deformable mirror by Family and get results from Laser Profiler

(3) Evaluate resulting parameter (Close to Flattop)

(4) The best two Chromosomes (Next Parents (i),(j))
2.3.11 Closed Control System for experiment

Profile Data

PC for control Deformable mirror and Evaluate resulting Laser Profile

CCD sensor (LBA-PC)

Laser Light source (THG: 263nm)
2.3.12 Results of spatial shaping with DM

- First test for computer-aided DM was done with He-Ne
  → **Flattop shaping OK!**

- Computer-aided DM for UV (THG)
  → **No problem (even for FHG:197 nm.)**

**Auto-Shaping (2500 steps)**
2.3.13 Both profiles shaping with Fiber Bundle

~ Transparent Cathode with Fiber Bundle ~

Pulse Stacking with 2,000 different Optical Passes

Fiber Bundle:
Length: 2.0 m
Bundle size: 12 mm
No. of Fibers: 1967
2.3.14 Results of shaping with Fiber Bundle

1. Results of spatial profiles with shaping
   - Spatially homogenizing is very strong with FB
     ➞ **Any kind of bad profile can be corrected!**
   - Pulse shaping & stretching with FB is pulse-stacking
     ➞ **Depend on the length and mapping of FB**
2. Results of **temporal** profiles with shaping

~ Pulse shaping result due to mainly **Pulse Stacking effect** ~

Width (FWHM): 16 ps
Fiber Bundle Length: 1 m
Mapping: Random
Input UV-pulse energy: down to 60 nJ
3. Avoiding interference spikes on *temporal* profiles
4. Closed Control System for Fiber Bundle with computer-aided Deformable mirror

I proposed as Ellipsoid Laser Shaping Technique for SLAC. (August 2005)
Short Summary of Laser shaping

• Shaping with computer-aided deformable mirror could generate Flattop. It is very flexible to optimize the spatial profile with genetic algorithm.

• Fiber Bundle is ideal as a 3D-shaper
  – It is very simple to shape: You have to optimize the length of the Bundle for aimed pulse duration: 15 ps ~ 1-m long
  – 3D-laser profile: It can generate ellipsoidal from any profile.
  – Short working distance: It needs to develop back illumination.
  – Laser fluence limit: Laser fluence @ 100 fs <1.5 mJ/cm²
    It is possible to use as 3D-shaper down to 60 nJ/pulse.

• Transparent cathode for shaping complex system with fixed fiber bundle & adjustable deformable mirror might have a lot of possibilities with fine tuning.
2.4 Long-term stabilization of laser

1. Passive Stabilization (completed)

Stabilizing *environmental & mechanical* factors

Reduction of:
- Optical damaging accidents
- Mechanical instability of optical components

2. Active Stabilization (in coming year)

- Automatic *boot-up*
- Automatic *adjustment* (AI-algorism)
- Automatic *Flash Lamp control* (Long-term Drift)
- Automatic *Re-gen Energy control* (shot-by-shot)

3. Down-Sizing (in future)
2.4.1 Humidification for avoiding charge-up

Environmental test clean room

Humidifier (pure water)

Constant Temperature & Humidity

Optimum Humidity

Charge-up

RH

55 %
2.4.2 Long-term stabilization with water-cooling

Water-cooling for crystal
Suppress thermal lens effect:

Water-cooling for Pockels Cell:
Suppress local heat-up:

Water-cooling for base-plate
Fix deformation of laser-box:

After Passive control

@THG (263 nm)

5 ~ 10 % (rms) → 0.7 ~ 1.3 % (rms)
2.4.3 Passive & Active stabilization of Oscillator

The most critical part of total laser stability

Oscillator: Instability of mode-locking

Active controlling optical pass of Pumping light source: Autoalign

New Oscillator is preparing

Replace conventional mirror holders with the thermal-deform-free ones
2.4.4. The present status of stability of UV-Laser Light Source

Present UV-laser stability:

0.2 ~ 0.3 % (rms) @ Fundamental

Long Term:
1 Month continuously

With new Oscillator, it will be 2 months.

5 ~ 10 % (rms)

After Passive control
0.7 ~ 1.3 % (rms)
2.4.5. The plan of stabilization of UV-Laser Light Source

2003
1. Complete environmental control
   Temperature, Humidity (RH: 55 %)
   New Clean Room & Optical Table

2004 Summer
2. Long-term stabilized Maintenance-free
   Laser light source was available!
   passive

2004 Winter
3. Realize Automatic Spatial & Temporal
   Shaping, Adjustment of Laser
   active

2005
4. Active stabilized Auto-Start-up
   Laser light source will be available!
3. Cavity & Laser incidence

3.1 Pillbox cavity

3.2 Results of Emittance Measurement

3.3 Effects of oblique incidence of a laser
3.1 Single-cell Test Cavity (First beam in 1999)

- Low Q \( (Q \sim 2800 \leftrightarrow 200\text{MV/m@80MW}) \)
  \[
  \frac{1}{Q} = \frac{1}{Q_0} + \frac{1}{Q_{\text{ext}}} = \frac{P_0 + P_{\text{ext}}}{\omega U}
  \]
  Shorter RF Pulse \( \rightarrow \) Higher Field Gradient

- Round and Thick Coupler Hole
  Relaxation of surface current concentration

- Pure Water Rinsing \( \rightarrow \) Dark Current Reduction
3.2 Results of Beam Emittance Measurement

(3.1-MeV E-Beam; direct after Gun; Double-Slit)

6.0 \( \pi \) mm mrad
May 2001

Laser S-Profile Improvement

2.3 \( \pi \) mm mrad
After Dec. 2001

3.3 Effects of oblique incidence of a laser to the cathode

Parameters (for both experiment & our simulation code)

- Maximum field on the cathode: 135 MV/m
- Initial RF phase: 85 degree
- First solenoid coil: 1560 Gauss
- Second solenoid coil: 780 Gauss
- Laser incident angle: 66 degrees
- Laser spot distribution: Gaussian like figure
- Laser spot radius: 0.3 mm (1s)
- Laser temporal length: 5 ps (FWHM)

Lowest x-emittance value of 2.3 \(\pi \text{mm\cdotmrad}\) was measured
3.4 Improvement with normal incidence of a laser to the cathode

A. **Square Pulse** with the optimal width ~ 20 ps

B. **Wave front** of laser pulse should reach at the same time to the cathode surface!

**Simulation!**
3.5 Experiment with normal incidence

1. Laser 3D-shape

Deformable Mirror

Flattop with DM

Pulse Width: 5 ps
3.5  Experiment with normal incidence

2.  Experimental setup

Test Linac: 28.8MeV after Acc.

- Experimental setup diagram
- Q-Scan setup
- Normal Incidence

Q-Triplet

UNIT: mm
3.5 Experiment with normal incidence

3. Experimental result

There is the difference between X- and Y-emittance!

Pulse width is far from the optimum value: 5 ps

Net Charge: 0.09 nC

@28.8 MeV

Profiler: Kodak; Lanex
3.5 Experiment with normal incidence

4. Why different?

- We calculated back the beam envelopes with using the transfer matrix of the accelerating structure and the Twiss parameters at the quadrupole magnet.

![Graph showing beam envelopes](attachment:image.png)

**The misalignment of electron beam at the entrance of accelerating structure.**

(Asymmetrical rf focusing forces in the input coupler)
4. Surface Treatment

- 4.1 Motivation of Surface Treatment
- 4.2 Chemical Etching
- 4.3 Chemical Etching with Cu-test pierce
- 4.4 Experimental Results
- 4.5 Etching-processed RF-gun cavity & High Field Test
- 4.6 Surface Diagnosis with Cartridge-type Cathode System (Transparent Cathode)
- 4.7 Diamond Cathode
4.5.1 Etching Process of RF-gun cavity

Chemical Etching
Cleaning cathode surface
No contamination
Least surface roughness

For high-field acceleration & high QE

Etching process
Cathode surface of RF gun after etching process
4.5.2 Chemical Etching test

$\text{H}_2\text{SO}_4$ & $\text{H}_2\text{O}_2$

Etching depth vs. Surface Roughness

Below etching depth $0.3\text{um}$, Surface Roughness does not change!
Etching depth vs. Etching processing time

Structure:
Below etching depth **0.3μm (2.5 min)**, Surface Roughness is reproducible.

Contamination:
We checked no chemical contamination on the surface with FTIR.

H₂SO₄ & H₂O₂
4.5.3 High Power Test for Etching-processed RF-gun cavity

Max. Cathode surface field: 190 MV/m

Max. surface field: 210 MV/m

QE: 1 x 10^{-2} \% (Cu-cathode)

With this high field: Laser incidence makes no rf-breakdown!
4.6 Surface Diagnosis with Cartridge-type Cathode System

- New cartridge holder accommodates up to 12 cartridges
- Development of transparent-type Diamond photocathode
- Easy to apply other kinds of photocathode
  - Ideal study for cathode surface physics
  - Rf Breakdown study
Cartridge-type Cathode

- Cathode plug
- RF contact (Cu-Be)
- Kovar Foil
- Vacuum Bellows
4.7 Diamond Photocathode

Characteristics of Diamond Photocathode

• Highest QE among all photocathodes (70%@125nm, however just 197nm-FHG available.)
• Wide band-gap semiconductor (Eg=5.5eV)
• NEA photocathode
• Surface is chemically stable (no need of UHV)
Diamond Photocathode

Dark Current of Diamond Photocathode

Dark Current [nC/bunch] vs Field Gradient [MV/m]

- Cs2Te
- Cu
- Diamond
4.5 High QE Photocathode

- Reflection-type Diamond: Cs terminated
- Reflection-type Diamond: H terminated
- Reflection-type Cs$_2$Te
- Transparent-type Cs$_2$Te

YAG5?  YAG4?

Wavelength (nm)
Summary

• Our purpose is generating the lowest emittance electron beam with long-term stability.

• Low Emittance Beam can be generated and evaluated with
  – Long-term laser stability: 0.7~1.3% (rms) for 1 Month
  – 3D-laser profile: Spatially Flattop & Rectangular Pulse
  – High Gradient Field: 190 MV/m @ Cathode
  – High Resolution Emittance Monitor: Resolution<1 πmm•mrad

• Cartridge-type Cathode System makes easy to study cathode surface physics & RF Breakdown.

• Transparent cathode for fiber bundle shaping system might have a lot of possibilities, but currently have discharge problems.