Generation and Acceleration of Low-Emittance, High-Current Electron Beams for SuperKEKB

High Energy Accelerator Research Organization
D. Sato, Tokyo Institute of Technology
SuperKEKB Upgrade and RF gun development

<table>
<thead>
<tr>
<th>KEKB obtained (e+ / e-)</th>
<th>SuperKEKB required (e+ / e-)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td></td>
</tr>
<tr>
<td>3.5 GeV / 8.0 GeV</td>
<td>4.0 GeV / 7.0 GeV</td>
</tr>
<tr>
<td><strong>Charge</strong></td>
<td></td>
</tr>
<tr>
<td>e- → e+ / e-</td>
<td>e- → e+ / e-</td>
</tr>
<tr>
<td>10 → 1.0 nC / 1.0 nC</td>
<td>10 → 4.0 nC / 5.0 nC</td>
</tr>
<tr>
<td><strong>Emittance [mm-mrad]</strong></td>
<td></td>
</tr>
<tr>
<td>2100 / 300</td>
<td>6 / 20</td>
</tr>
</tbody>
</table>

5 nC 10 mm-mrad electron beam generated by RF gun. + 10mm-mrad emittance preservation is required.

Quasi–travelling side couple RF-Gun with Yb laser system. (2013)

Preliminary test using DAW RF-Gun with Nd laser system due to earthquake. (2011)
RF-Gun development strategy for SuperKEKB

• Cavity: Strong electric field focusing structure
  – **Disk And Washer (DAW)** => 3-2, A-1(test)
  – **Quasi Traveling Wave Side Couple** => A-1
  => Reduce beam divergence and projected emittance dilution

• Cathode: Long term stable cathode
  – Middle QE (QE=10^{-4} \sim 10^{-3} @266nm)
  – Solid material (no thin film) => Metal composite cathode
    => Started from LaB$_6$ (short life time)
    => **Ir$_5$Ce has very long life time and QE>10^{-4} @266nm**

• Laser: Stable laser with temporal manipulation
  – LD pumped laser medium => Nd / Yb doped
  – Temporal manipulation => Yb doped
    => Minimum energy spread
• RF-Gun
  – Design of RF-Gun cavity
    • Quasi travelling wave side couple
  – Cathode
  – Laser
  – Test stand and schedule
RF-Gun for 5 nC

- Space charge is dominant.
  - Longer pulse length: 20 - 30 ps
- Stable operation is required.
  - Lower electric field: < 120 MV/m
- Focusing field must be required.
  - Solenoid focus causes the emittance growth.
  - Electric field focus preserve the emittance.

Emittance vs. Laser pulse length graph:
- Total emittance
- Space charge emittance
- RF emittance

Types of coupled cavities:
- Cylindrical coupled cavity: BNL
- Annular coupled cavity: Disk and washer or Side couple
Electric focusing field by narrow gap

Closed gap makes focus field
Side coupled cavity is one candidate (or DAW / ACS / CDS …)

This structure has focusing field.
Long drift space is problem.
Design of a quasi traveling wave side couple RF gun

Normal side couple structure

Quasi traveling wave side couple structure

Quasi traveling wave side couple has stronger focusing field
Quasi traveling wave side couple RF gun

This RF gun has total of seven acceleration cavities. These are divided into two standing wave structure of 3 and 4 side coupled cavities respectively.

Cathode cell
To avoid beam defocusing, emittance growth and field concentration, a lot of parameters were searched for design.

Maximum E-field at surface: 120 MV/m

Maximum E-field at surface: 100 MV/m

Emittance: 5.5 mm-mrad @ 5 nC

This RF gun can generate 10 nC beam
Beam tracking simulation result

5 nC
Emittance 5.5 mm-mrad

Gun Exit
Size 0.4 mm

Energy spread 0.6%
Bunch shape

10 nC

Energy [MeV]

Emittance [mm-mrad]

Size [mm]

Energy dispersion [%]

Time = 2.48098e-009
RF-Gun comparison

Quasi traveling wave side couple RF gun
(100 MV/m, 6 mm-mrad, 13.5 MeV)

DAW-type RF gun
(90 MV/m, 5 mm-mrad, 3.2 MeV)

BNL-type RF gun
(120 MV/m, 11.0 mm-mrad, 5.5 MeV)

Beam Size
Cavity design

Field calculation

k : 3.0 %

beam

coupling cavities

accelerating cavity

cathode

No reflection to klystron

90 deg hybrid

RF
Mechanical design and manufacturing
• RF-Gun
  – Design of RF-Gun cavity
  – Cathode
    • Advantage of LaB6
    • Measurement equipment of quantum efficiency
    • Laser cleaning & Heat treatment
  – Laser
  – Test stand and schedule
Cathode: Advantage of LaB$_6$ or Ir$_5$Ce

Justin Jimenez, A Systematic Cathode Study, Ph.D Thesis, Monterey, California

- Low Workfunction (2.8 eV) and enough QE ($10^{-4}$) at room temperature.
- Inactive in air
- Recover by heating or laser cleaning

Best choice for SuperKEKB 5 nC long time operation

The thermocathodes can also be used as photoemitters [13]. LaB$_6$ should be noted as a promising photoemitter [14], which has a quantum yield of about $10^{-3}$ at a laser wavelength of 266 nm and $4\cdot10^{-4}$ at 532 nm for face (100).


Cathodes for Electron Guns
G. I. Kuznetsov
Ir$_5$Ce Cathode

Quantum efficiency improvement by Laser cleaning

Lower energy density is enough to activate Ir$_5$Ce

No oxidization is observed

QE Enhancement of IrCe cathode
• RF-Gun
  – Design of RF-Gun cavity
  – Cathode
  – *Yb Laser for spatial & temporal manipulation.*
  – Test stand and schedule
Energy spread reduction using temporal manipulation

Energy spread of 0.1% is required for SuperKEKB synchrotron injection.
### Properties of laser medium

#### Nd-doped
- 4-state laser is easy to operate.
- High power pump LD is available.
- Large crystal is available
- Pulse width is determined by SESAM.
  
  \[ \tau \sim 200\mu s, 40\% \]

#### Yb-doped
- Wide bandwidth => pulse shaping
- Long fluorescent time => High power
- Fiber laser oscillator => Stable
- Small state difference
- ASE
- Absorption
  
  \[ \tau \sim 900\mu s, 40\% \]

#### Ti-doped
- Very wide bandwidth
- High breakdown threshold
- Low cross section
- Short fluorescent time => Q-switched laser is required for pumping

<table>
<thead>
<tr>
<th>Material</th>
<th>Nd:YAG</th>
<th>Yb:YAG</th>
<th>Ti:Sapphire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>1064nm</td>
<td>1030nm</td>
<td>660-1100nm</td>
</tr>
<tr>
<td>Fluorescent time</td>
<td>230\mu s</td>
<td>960\mu s</td>
<td>3.2\mu s</td>
</tr>
<tr>
<td>Spectral width</td>
<td>0.67nm</td>
<td>9.5nm</td>
<td>440nm</td>
</tr>
<tr>
<td>Fourier minimum</td>
<td>2.48ps</td>
<td>165fs</td>
<td>2.59fs</td>
</tr>
<tr>
<td>Pulse width</td>
<td>2.48ps</td>
<td>165fs</td>
<td>2.59fs</td>
</tr>
<tr>
<td>Wavelength</td>
<td>807.5nm</td>
<td>941nm</td>
<td>488nm</td>
</tr>
<tr>
<td>Spectral width</td>
<td>1.5nm</td>
<td>21nm</td>
<td>200nm</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>76%</td>
<td>91%</td>
<td>55%</td>
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Ti:Sapphire laser system.
Yb fiber & thin disk hybrid laser system

1 nJ @ 1035 nm

Yb-doped fiber oscillator

51.9 MHz

Transmission Grating Stretcher

10 MHz

EO fiber Module

Yb-doped fiber pre amplifier

Synchronization system

Yb-doped fiber main amplifier

30 ps

EO Pulse picker

Yb-doped fiber amplifier

25 Hz 2 bunch

Yb:YAG thin-disk 6-pass amplifier

2856 MHz trigger From Accelerator

Yb:YAG thin-disk 5-pass amplifier

RF GUN

258 nm

Yb:YAG thin-disk 5-pass amplifier

515 nm

BBO

SHG

SHG

QE = 10^{-4} \rightarrow A few mJ @ 258nm, 50Hz is required.
Yb Fiber Laser

Transmission grating pair

Yb Fiber Main Amplifier

Yb Fiber Pre Amplifier

From Yb Fiber Oscillator

Pulse Picker EO

Stretcher
Thin-disk multi-pass amplifier

- 0.5 mmt Yb:YAG thin-disk
- 3-stage 4-6 multi-pass amplifier

A few mJ @ 258nm
• RF-Gun
  – Design of RF-Gun cavity
  – Cathode
  – Laser
  – Test stand and schedule
    • 3-2 RF-Gun for preliminary test & PF injection
    • A-1 RF-Gun
A-1 RF gun

- Quasi-travelling wave side couple RF-Gun
- Yb based laser system

Chicane for bunch compression
30ps => 10ps
Installed RF gun

RF

Cathode

90 deg Hybrid

Laser port
A-1 RF gun results

5.6 nC bunch charge was observed.

RF gun

A1 sector at KEK linac

beam size measurement for Q-scan

Q-scan emittance measurement

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
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<tr>
<td>32.7 ± 3.1 mm-mrad</td>
<td>10.7 ± 1.4 mm-mrad</td>
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Emittance preservation
Emittance preservation

Longer bunch can reduce space charge effect inside RF-Gun and also CSR at J-ARC.

Due to mis-alignment:
- Dispersion
- Short range wakefield

Emittance growth after 500 m

\[ \sigma_E < 0.1 \% \]

Initial offset

<table>
<thead>
<tr>
<th>SuperKEKB</th>
<th>J-ARC R_{56}</th>
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<td>Bunch charge</td>
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<td>10 / 1.0 nC / 1.0 nC</td>
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<td>Beam emittance</td>
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<tr>
<td>[nH]</td>
<td>[nH]</td>
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<td>2100 μm / 300 μm</td>
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High charge low emittance is required for SuperKEKB.
Hardware for emittance preservation

• **Alignment**
  – Continuous monitor (HLS, Wire)
    + Active mover
  – Beam based alignment (Higher mode measurement)

• **Temporal manipulation**
  – Laser pulse shaping
  – Bunch compression

• **Beam diagnostics for offset injection**
  – RF Deflector

*Developed by SLAC*
Preliminary test for higher order transverse wakefield from accelerating structure.

Synchronized RF 8~12 GHz (Base RF: 10.38 MHz)

Magic T
Summary

• RF-Gun cavity
  – Quasi travelling wave side couple structure.

• Cathode
  – Room temperature $\text{Ir}_5\text{Ce}$ cathode has enough QE.
  – Laser cleaning & laser injection angle is effective.
  – R&D for the QE improvement.

• Laser & control
  – Yb based laser system : A-1 RF-Gun
    • Yb-fiber : Precise RF synchronization.
    • Yb-disk amplifier: High power output.
    • Temporal manipulation Under experiment.
  – Stability / Control: Improved but not enough.

• RF gun comissioning
  – 5.6 nC bunch charge was generated by this RF gun.

• Emittance Preservation
  – Alignment / Bunch compression / Monitor etc.