コンパクトERLにおけるビームロス低減のためビームハロー観察及び解析

Beam halo observation and examination for beam loss reduction at the Compact ERL

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Introduction
Current status of cERL

- FY2015 achievements
  - 1 mA high-average-current operation
  - Total beam losses less then 0.1%*
  - Successful bunch compression
  - Successful commissioning of laser Compton Scattering (LCS) system

- For detailed information refer to:
  - S. Sakanaka, 1 mA operation, WEOM15
  - M. Shimada, beam optics, TUP062 and TUP063
  - T. Miyajima, orbit correction, TUP064
  - K. Harada, rastering system, MOP079

<table>
<thead>
<tr>
<th>Typical parameters</th>
<th>Design</th>
<th>In operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>35 MeV</td>
<td>19.9 MeV</td>
</tr>
<tr>
<td>Injector energy</td>
<td>5 MeV</td>
<td>2.9 – 6.0 MeV</td>
</tr>
<tr>
<td>Gun high voltage</td>
<td>500 kV</td>
<td>390 – 450 kV</td>
</tr>
<tr>
<td>Maximum current</td>
<td>10 mA</td>
<td>1 mA</td>
</tr>
<tr>
<td>Bunch length</td>
<td>1 – 3 ps</td>
<td>1 – 3 ps (usual)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.15 ps (compressed)</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>1.3 GHz</td>
<td>1.3 GHz (usual)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>162.5 MHz (for LCS)</td>
</tr>
</tbody>
</table>

Total path length ~ 120 m

* For circulating 1-ma CW beam
Introduction
Future plan and nearest R&D of cERL

- **1st stage** of the future light source at KEK is a low-emittance electron storage ring of energy 3 GeV (KEK-LS) [more details K. Harada, WEOM16]
- **2nd stage** of the plan is linac-type light source establishment:
  - CW-XFEL (high-repetition-rate FEL linac)
- **Industrial application**
  - EUV-FEL (FEL for Extreme Ultraviolet lithography) [see N. Nakamura, TUP074]

R&D of ERL technologies in KEK is still very urgent task!

- **Possible applications of cERL:**
  - High-power THz light source [see Y. Honda, MOP076]
  - High-flux LCS facility [see T. Akagi, MOP057]
- **Nearest R&D include:**
  - Lower emittance (< 1 mm mrad) establishment at higher bunch charges (7.7 pC)
  - Beam current increase up to 10 mA
- **Current increase scheme:**
  1. Beam repetition rate increase
  2. Accelerator adjustment (optics tuning, orbit corrections (especially in the injector line), radiation surveys, beam loss estimation)
  3. Beam halo collimation (to reduce the beam losses along the beam line)

Beam loss mitigation is indispensible for the current increase!
Introduction
Reasons of the beam loss in cERL

- **Beam dynamics:**
  - Space charge (negligible for 0.2 – 0.3 pC/bunch)
  - Intrabeam scattering
  - Touschek scattering (~0.04 pA/m)*

- **Design-related:**
  - Beam line elements misalignment
  - Kicks from steering coils

- **Errors:**
  - Improper timing
  - Laser or RF cavity phase shift

- **Electron gun:**
  - Longitudinal bunch tail (order of a few uA/m)**
  - Scattered light on cathode
  - Field emission from the gun

- **Vacuum system:**
  - Residual gas scattering (~0.76 pA/m)*
  - Ion trapping

- **SRF cavities:**
  - Dark current
  - Kicks from input / HOM couplers

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Introduction

Beam halo formation mechanism

- **Subject:** beam halo as a source of the beam loss. The beam halo is known to be a collection of particles of any origin and behavior which lies in the low density region of the beam distribution far away from the core*.

- **Reason:** longitudinal bunch tail originated at the photocathode transferred into the transverse plane.

- **Mechanism:** we guess it occurs due to rf field kicks. These kicks are a complex effect of:
  - Injector cavities misalignment
  - Steering coils influence on the beam trajectory inside the cavity

**Transverse offset at the collimators**

**Beam loss reduction in the recirculating loop**

- **Goal:** of the beam halo measurements and simulations reported here is to check and to confirm the tail transformation hypothesis of beam halo formation and to explore other possibilities of beam halo formation and beam loss issues in cERL.

Beam halo measurement

Settings

<table>
<thead>
<tr>
<th>Settings</th>
<th>Burst</th>
<th>Long pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro pulse duration</td>
<td>1 μs</td>
<td>1.5 ms</td>
</tr>
<tr>
<td>Macro pulse frequency</td>
<td>5 Hz</td>
<td>0.6 Hz</td>
</tr>
<tr>
<td>Integration time</td>
<td>10 μs</td>
<td>2 ms</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>0.2-0.3 pC</td>
<td>2.6 fC</td>
</tr>
<tr>
<td>Average current</td>
<td>1.5 nA</td>
<td>3 nA</td>
</tr>
<tr>
<td>Peak current</td>
<td>300 μA</td>
<td>15 nA</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>1.3 GHz</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>Beam energy</td>
<td>2.9 - 20 MeV</td>
<td>20 MeV</td>
</tr>
</tbody>
</table>

- CAM8 placed in the merger section, where the dispersion impacts to the halo formation
- CAM 16 of the 1\textsuperscript{st} arc is also located in the dispersive section. Therefore, some particles with an energy spread could be observed
- CAM17 picks up the beam profiles in the place with big betatron oscillations
- Location of CAM21A (before the LCS system) coincides with the loss point
- COL1, 2 helpful to reduce the beam loss in the recirculating loop, are in the merger section
Beam halo measurement

Workflow

1. Adjust the trigger delay so that only one macro pulse 1 μs (1.5 ms\(^1\)) could be captured during one camera shutter pulse 10 μs (2 ms\(^1\))
2. Set the camera gain to maximum (22 dB)
3. Then the sets of beam halo profiles are collected automatically with macro pulse frequency 5 Hz (0.6 Hz\(^1\))
4. Insert the collimators
5. Repeat steps 1 – 3

\(^1\) For long pulse mode
Beam halo measurement
CCD camera optics

- CAM8 YAG: φ28, L1=21, L2=337, L3=420, mirror2: φ60, lens: f100-φ30
- CAM16 YAG: 40x20, L1=27, L2=229, L3=161, mirror2: φ50, lens: f50-φ28
- CAM21A YAG: φ28, L1=21, L2=229, L3=139, mirror2: φ50, lens: f50-φ28
Beam halo measurement

YAG screen setup

CAM16

CAM8,17,21A

inner wall of screen holder

YAG

40x20

CCD area (659x493 pixels)

YAG & screen cover

inner wall of screen holder
23/Feb, burst mode, gain 22 dB, int. time 10 us

23/Feb, burst mode, gain 22 dB, int. time 10 us

9/Mar, long pulse mode, gain 22 dB, int. time 10 us

YAG screen light reflected in the YAG screen holder captured by CCD
CAM17
9/Mar, long pulse mode, gain 0 dB, int. time 10 us

COL OUT

COL IN

Pixel

CAM21A
9/Mar, long pulse mode, gain 22 dB, int. time 10 us

COL OUT

COL IN

Pixel
Beam halo measurement
Core-halo ratio estimation

- Core / halo / background area selection (manually)
- Scaling

\[
\text{Intensity(halo)} = 12.5893 \times 20 \times \text{Intensity(core)}
\]

Gain 22 dB vs Gain 0
ND filter 20

<table>
<thead>
<tr>
<th>Place of observation</th>
<th>Core, %</th>
<th>Halo, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAM8 (merger)</td>
<td>99.45</td>
<td>0.55</td>
</tr>
<tr>
<td>CAM16 (1st arc)</td>
<td>99.37</td>
<td>0.63</td>
</tr>
<tr>
<td>CAM17 (straight sect.)</td>
<td>99.64</td>
<td>0.36</td>
</tr>
<tr>
<td>CAM 21A (before LCS)</td>
<td>99.48</td>
<td>0.52</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>99.49</td>
<td>0.51</td>
</tr>
</tbody>
</table>
Beam halo measurement
Lessons learned from beam halo measurements

- After the proper data processing, vertical halos* at all camera locations were observed clearly. On the contrary, there weren’t any vertical halos at the profiles, captured when collimators were in
- Vertical beam halo can be truncated using collimation system effectively. The beam loss reduction in the recirculating loop was simultaneous with the vertical halo truncation. We believe it is a good confirmation of the effectiveness of the beam tuning together with the collimation system
- Core-halo ratio estimation, based on the profiles measured at different CCD camera gain settings, gives about 0.5% for vertical beam halo

* Note, that only vertical halos issues observed during the measurement are discussed in this study. Of course, there could be any other unobserved beam halos at any other beamline locations
Beam halo simulation
Cathode temporal response

- The probability density function of longitudinal distribution is obtained from the GaAs bulk photocathode measurement*
- The measurement data is fitted by the convolution integral of Gaussian core with one or more electron retardation mechanisms

\[
S(t) \propto \exp\left(\frac{\sigma_t^2}{2\tau^2}\right) \exp\left(-\frac{t-t_0}{\tau}\right) \text{erfc}\left(\frac{\sigma_t}{\sqrt{2}\tau} - \frac{t-t_0}{\sqrt{2}\sigma_t}\right),
\]

\[
S_{\text{fast}}(t) = \exp\left(\frac{\sigma_t^2}{2\tau_f^2}\right) \exp\left(-\frac{t-t_0}{\tau_f}\right) \text{erfc}\left(\frac{\sigma_t}{\sqrt{2}\tau_f} - \frac{t-t_0}{\sqrt{2}\sigma_t}\right),
\]

\[
S_{\text{slow}}(t) = \exp\left(\frac{\sigma_t^2}{2\tau_s^2}\right) \exp\left(-\frac{t-t_0}{\tau_s}\right) \text{erfc}\left(\frac{\sigma_t}{\sqrt{2}\tau_s} - \frac{t-t_0}{\sqrt{2}\sigma_t}\right),
\]

\[
S(t) = S_{\text{fast}}(t) + S_{\text{slow}}(t).
\]

Beam halo simulation
Initial particle distribution

**Simulation input parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of particles</td>
<td>1E4</td>
</tr>
<tr>
<td>Beam energy</td>
<td>2.9 – 20 MeV</td>
</tr>
<tr>
<td>Total charge</td>
<td>0.3 pC / bunch</td>
</tr>
<tr>
<td>RF frequency</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>Laser spot diameter</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>Bunch length</td>
<td>3 ps</td>
</tr>
</tbody>
</table>

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**Transverse distribution**

(\(\varphi=1.2\) mm)

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**Longitudinal distribution**

(Gaussian + tail)

From cathode to main RF cavity exit → GPT

From main RF cavity exit to dump → ELEGANT
Beam halo simulation
Simulation conditions

• To reproduce the rf field kicks in the simulation:
  1. Set up the optics (e.g. the K values of the quadrupole magnets)
  2. Set up the fields of steering coils
  3. Set up the injector cavities offset

Layout of cERL injector

Injector cavities offset
Beam halo simulation
Core-halo ratio estimation

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<td>0.93</td>
</tr>
<tr>
<td>CAM16 (1st arc)</td>
<td>99.43</td>
<td>0.57</td>
</tr>
<tr>
<td>CAM17 (straight sect.)</td>
<td>99.50</td>
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<td><strong>0.63</strong></td>
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</table>
Beam halo simulation
Lessons learned from beam halo simulation

- The lower part of the halo at CAM8 is very likely caused by longitudinal bunch tail transferred into transverse plane
- Upper part of this halo seems to be due to the injector cavities rf field kicks
- The statement above is opposite for CAM16, 17, and 21A (the upper part is due to the tail and lower part due to the rf field kicks)
- The beam core-halo ratio estimations from the simulated profiles yield the values of almost the same order with estimations from the measured profiles. That once again confirms the correctness of our halo formation hypothesis
The next step of cERL R&D is low-emittance and high bunch charge operation, while the average beam current is increased. Thus, the study of the beam halo formation mechanisms is indispensable for overall beam loss reduction.

As we learned from the beam tuning experience, the most likely cause of the beam halo in cERL is longitudinal bunch tail originated at photocathode transferred into the transverse plane.

Our guess, that it occurs due to rf field kicks, find the experimental and computational evidences. Therefore we succeed in beam loss mitigation utilizing the collimation system.

However, a further beam loss elimination with achieving extremely low emittance is inextricably linked to the reduction of the longitudinal bunch tail originating in the photocathode.

One more possible but still unexplored halo reason is an influence of the input coupler of injector cavity.

Due attention should be paid to space charge effect when the bunch charge will be increased.
御静聴ありがとうございました