Optics Design for the Commissioning of the Compact ERL Recirculation Loop

ERL 2013
The 53th ICFA Advanced Beam Dynamics Workshop on Energy Recovery linac

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**Outline**

- **Introduction of Compact ERL**

- **Start-to-end (S2E) simulation for the Compact ERL (cERL)**
  - Optimization of injector and recirculating loop
  - Particle tracking simulation including space charge or CSR wake effects

- **Applications**
  - Laser inverse Compton scattering
  - THz-CSR and bunch compression

- **Beam loss and field-emission**

- **Summary**
Site and construction of cERL
Final Goal of cERL, double Loop

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy</td>
<td>5-10 MeV</td>
</tr>
<tr>
<td>Full energy</td>
<td>245 MeV</td>
</tr>
<tr>
<td>Electron charge</td>
<td>77 pC</td>
</tr>
<tr>
<td>Average current</td>
<td>10-100 mA</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>&lt;1 mm-mrad</td>
</tr>
<tr>
<td>Bunch length</td>
<td>1-3 ps</td>
</tr>
<tr>
<td>Momentum spread</td>
<td>&lt;1e-3</td>
</tr>
</tbody>
</table>

Why did we choose a double loop circulator?
It is for saving construction area, number of accelerator cavities, running cost of the refrigerators.
First commissioning of recirculation Loop

- Only two superconducting cavities are installed.
- Circulating energy is 20 – 35 MeV with injection energy of 3.4 - 5 MeV
  - Revolution time depends on the circulating energy.
- Tunable range of the circumference is ±25 mm.
  - Couples of steering magnets in the arcs (±20mm), Chicane in the straight line (±5mm)
- Applications
  - X and gamma-ray source by Laser inverse Compton scattering (LCS)
  - THz source of CSR from short electron bunch
Start-to-end simulation

- **General Particle Tracer, GPT**
  - 6D tracking code with mesh based 3D space charge effect
  - CSR wake effects can be calculated but it costs huge calculation time...

- **“elegant”**
  - Matching of the linear optics is based on the transport matrix.
  - 1D CSR wake with transient effect and over a drift
  - lacking space charge effects

- **Injector → Switch point A**
  - Optics is optimized by GPT

- **Switch point A → Dump**
  - Optics is optimized by elegant
  - Particle Tracking
    - “elegant” to simulate CSR wake effect
    - GPT to simulate space charge effect
Layout and optimization of injector

1. Minimization of emittance at the switching point A
2. Matching with circulator loops

Point A: Switching point, 35MeV
Target of Twiss parameters
-2 < $\alpha_x$ < -0.36, 2.63 < $\beta_x$ < 8 m, -0.33 < $\alpha_y$ < 0, 10.2 < $\beta_y$ < 24.4 m
Results of optimization of injector

Old layout ($\Delta z_Q = 0.1 \text{ m}$): 0.691 mm mrad
Present layout ($\Delta z_Q = 0.5 \text{ m}$): 0.262 mm mrad

<table>
<thead>
<tr>
<th>parameter</th>
<th>2 k particles</th>
<th>100 k particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{nz}$ (mm-mrad)</td>
<td>0.262</td>
<td>0.307</td>
</tr>
<tr>
<td>$\epsilon_{ny}$ (mm-mrad)</td>
<td>0.261</td>
<td>0.361</td>
</tr>
<tr>
<td>$\sigma_z$ (mm)</td>
<td>0.846</td>
<td>0.873</td>
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<tr>
<td>$\gamma$</td>
<td>69.5014</td>
<td>69.497</td>
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<tr>
<td>$\sigma_\gamma$</td>
<td>0.0290783</td>
<td>0.0192432</td>
</tr>
<tr>
<td>$\beta_x$ (m)</td>
<td>2.67319</td>
<td>2.59521</td>
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<td>$\beta_y$ (m)</td>
<td>2.11744</td>
<td>2.03121</td>
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<tr>
<td>$\alpha_x$</td>
<td>-0.601</td>
<td>-0.945</td>
</tr>
<tr>
<td>$\alpha_x$</td>
<td>-0.179</td>
<td>0.305</td>
</tr>
</tbody>
</table>

2k particles is used for optics optimization
100k is the final data
Electron charge: 7.7pC
Optical functions of circulating loop

- Just after acceleration up to 35 MeV to dump.
- 5 MeV and 35 MeV pass through the same transport line.
  - Optics is optimized for the lower energy beam.
- Arc section is based on TBA with isochronous condition.
  - Triplet between the bending magnets is DFD to make it easy to match the optical functions.
Effects of space charge on beam size

- Particle tracking is performed with GPT.
- Horizontal beam size increase at the dumpline.
- There are no significant effects of space charge before energy recovery.
Electrons in the core and surroundings feel a different focus strength.

Transverse emittance growth is caused by twist of the phase space distribution.
Space charge effect increase the energy spread and bunch length
Effects of CSR wake on horizontal beam size and emittance

- Energy spread almost doubles after energy recovery but it still less than 0.001.
- There are no significant effects of CSR wake in the recirculating loop.
Applications of cERL

- Collision point of LCS
- Laser optical cavity
- THz-CSR from short electron bunch
- Bunch length is less than 150 fs
Laser inverse Compton scattering

Nominal rms beam size @ collision point

\[ \sigma_x = 12.8 \, \mu \text{m}, \quad \sigma_y = 6.6 \, \mu \text{m} \]

@ \( \varepsilon_{nx} = \varepsilon_{ny} = 0.3 \, \text{mm mrad} \)

\( \sigma_x = 13.8 \, \mu \text{m}, \quad \sigma_y = 10.7 \, \mu \text{m} \)
Bunch compression for THz light source

\[ \sigma_z = 2 \text{ ps} \]
\[ \sigma_p/p = 0.002 \]

\[ \sigma_z = 2.13 \text{ ps} \]
\[ \sigma_p/p = 0.00425 \]

Sextupole OFF
\[ \sigma_z = 686 \text{ fs} \]
\[ \sigma_p/p = 0.00425 \]

Sextupole ON
\[ \sigma_z = 140 \text{ fs} \]
\[ \sigma_p/p = 0.00454 \]

Initial Parameter
- Bunch charge: 77 pC
- Injection energy: 5.5 MeV
- \( \sigma_p/p = 0.002 \)
- \( \epsilon_{nx} \) and \( \epsilon_{nv} \): 1 mm mrad

Main SC cavities
- RF volt. 15 MV x 2 cav
- RF phase: 15.8 deg

Tracking code: elegant
- 1D CSR wake, no Space Charge
- Physical aperture larger than $5\sigma$ satisfies beam loss rate less than $1\times 10^{-6}$.
- Thanks to the large apertures after energy recovery, there is no significant beam loss even a deteriorated electron beam ($\sigma_p/p=0.002$, $\varepsilon_{nx}=\varepsilon_{ny}=10\text{mm-mrad}$).
Loss of field emitted electrons

(a) 0 - 15 MeV

(b) 15 - 30 MeV

Downstream of the cavity
Upstream of the cavity

Distribution of lost field-emitted electrons (N=3000) with accl. field of 15MV/m

Additional radiation shields were installed based on the results of a particle tracking simulation
Summary

- **Start-to-end simulation**
  - S2E simulation is performed to estimate the collective effect (space charge and CSR wake) on the commissioning energy of cERL.
  - Tracking results show there is no significant effect on the beam.

- **Applications**
  - Effects of alignment of Q magnets and space charge effect on beam size are simulated at the collision point of LCS.
  - Rms bunch length can be compressed less than 150 fs for THz-CSR light source even the commissioning mode of 35 MeV.

- **Beam loss**
  - Beam loss due to physical aperture and loss of field-emitted electron are evaluated.
  - The simulation results is reflected in the design of radiation shielding.

**Commissioning of recirculation loop will start this December!**
Thank you for your attention