SRF System for Coherent electron Cooling

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Content

Introduction
  Coherent electron Cooling
  Requirements for the CeC
  SRF system layout

112 MHz QWR SRF Gun
  Quarter Wave Resonator (QWR)
  SRF Gun parameters
  Gun Setup
  Gun Performance
  Multipacting

500 MHz bunching cavities
  Bunching Cavities

704 MHz accelerating cavity
Introduction
Coherent electron Cooling

Cooling:
reduces beam phase space volume, emittance and momentum spread in order to improve beam quality.

How does it work:
- In the modulator, each hadron induces density modulations in electron beam;
- Density modulation is amplified in the high-gain FEL;
- In the kicker, hadrons interact with the self-induced electric field of the electron beam and receive energy kicks toward their central energy;
- The process reduces the hadron’s energy spread, i.e. cools the hadron beam.
Goal:

demonstration of longitudinal (energy spread) cooling of a single bunch of 40 GeV/u Au ions in RHIC

In order for the CeC to work, it is required for the electron and hadron beams to have the same velocity:

\[
\gamma_e = \gamma_h = \frac{1}{\sqrt{1-(v/c)^2}}
\]

\[
E_e = \gamma_h \cdot m_e c^2 \approx 22 \text{ MeV}
\]
Introduction
SRF system layout

From right to left:

- The SRF gun operating at 112 MHz will generate 2 MeV high-charge (several nC), low repetition rate (78 kHz) electron beam;
- Two single cell normal conducting bunching cavities operating at 500 MHz frequency will provide required energy chirp in the beam creating velocity difference along the bunch;
- The 704 MHz 5-cell SRF cavity (BNL3) is used to achieve desired energy of 22 MeV.
112 MHz QWR SRF Gun

S. Belomestnykh et al., SRF and RF systems for CeC PoP experiment
112 MHz QWR SRF Gun
Quarter Wave Resonator (QWR)

Frequency was chosen to be 112 MHz because:

- It is a harmonic of RHIC 28 MHz RF system;
- Low frequency ⇒ long bunches ⇒ reduced space charge effect;
- Short accelerating gap ⇒ almost constant field;
112 MHz QWR SRF Gun
SRF Gun parameters

Table: Parameters of the SRF Gun

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>112 MHz</td>
</tr>
<tr>
<td>Geometry factor</td>
<td>38.2 Ohm</td>
</tr>
<tr>
<td>R/Q</td>
<td>126 Ohm</td>
</tr>
<tr>
<td>Quality factor w/o cathode</td>
<td>3.5 \cdot 10^9</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>4.5 K</td>
</tr>
<tr>
<td>Accelerating voltage</td>
<td>1.5 to 2.0 MV</td>
</tr>
</tbody>
</table>

Reminder:

Quality factor: \( Q_0 = \frac{\omega_0 U}{P_c} \)

Geometry factor: \( G = \frac{\omega_0 \mu_0 \int \frac{|H_0|^2}{\mu} dV}{\iint |H_0|^2 dA} \)

Shunt Impedance: \( R = \frac{V_{rf}^2}{P_{loss}} \)
Fundamental RF power coupling and fine frequency tuning is accomplished via a coaxial beam pipe at the beam exit port;

With the travel of ±2 cm, the tuning range will be ~ 4 kHz;

A small cathode puck is inserted inside the stalk and can be replaced when

S. Belomestnykh et al., Commissioning of the 112 MHz SRF Gun
When turning on the RF power strong multipacting was observed, which substantially reduced quantum efficiency of the cathode.

- 3.7 nC beam charge was observed during the commissioning;
- achieved cavity voltage was 1.2 MV;
- duration of the laser pulse was 1 ns.
Multipactor discharge (multipacting) is a resonant process in which an electron avalanche builds up within a small region of the cavity surface and is determined by the following factors:

- Electric field levels;
- Geometry of the cavity;
- Material properties — Secondary Emission Yield (SEY).

An electron avalanche absorbs large amounts of RF power and deposits it as heat ⇒ lower quality factor.
112 MHz QWR SRF Gun
Multipacting Simulations

Calculate EM fields
Define emitting surface
Define SEY
Analyze EF and Trajectories

![Gun diagram](image)

Graph: Enhancement factor vs. Gap Voltage (kV)

- 1st and 2nd order MP
Perform multipacting simulations with all factors present during the experiment: cathode position, external magnetic field, etc.;

Continue improvement of the emittance and achieve higher energy during Run 2017.
500 MHz bunching cavities

704 MHz SRF booster cryomodule

Normal conducting bunching cavities

112 MHz QWR SRF gun

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The reference particle \((\varphi = 0, \Delta W = 0)\) arrives at the center of a cavity when the voltage is rising in time and is zero \(\Rightarrow\) zero average gain;

The buncher cavity delivers a phase-dependent kick which changes an upright ellipse to a tilted one;

After passing a proper drift space, the ellipse is rotated by 90° in phase space.
500 MHz bunching cavities
CeC Bunching Cavities

**Table:** Parameters of the 500 MHz bunching cavity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Frequency</td>
<td>500 MHz</td>
</tr>
<tr>
<td>Accelerating voltage</td>
<td>0.3 MV</td>
</tr>
<tr>
<td>R/Q</td>
<td>178.5 Ohm</td>
</tr>
<tr>
<td>Geometry Factor</td>
<td>38.2 Ohm</td>
</tr>
<tr>
<td>Quality Factor</td>
<td>31000</td>
</tr>
</tbody>
</table>

CeC Run’16 eLog
704 MHz accelerating cavity

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704 MHz accelerating cavity
BNL3 Cavity

Table: Parameters of the BNL3 cavity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>RF Frequency</td>
<td>704 MHz</td>
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<tr>
<td>Accelerating voltage</td>
<td>20 MV</td>
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<tr>
<td>R/Q</td>
<td>506.3 Ohm</td>
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<tr>
<td>Geometry Factor</td>
<td>283 Ohm</td>
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<tr>
<td>Quality Factor</td>
<td>$2 \cdot 10^{10}$</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>1.9 K</td>
</tr>
</tbody>
</table>

Performance

- Desired beam energy of 22 MeV was not achieved during the experiment due to the strong heat load on the cryogenic system accompanied by substantial radiation levels; Most likely the cavity was contaminated during installation.
- The fast piezoelectric tuner was damaged and stepper motor driven broke during operation.
Conclusion

- The CeC PoP SRF system commissioning has started;
- It has been proven experimentally that SRF gun can operate with high efficiency $CsK_2Sb$ photocathode and generate CW electron beam with record-high charge per bunch;
- Most systems of CeC PoP (instrumentation, SRF gun, 500 MHz cavities, magnets) operated without substantial problems;
- To be continued in 2017...
Thank you for your attention! Questions?
References

- V.N. Litvinenko et.al., *Coherent Electron Cooling Demonstration Experiment*, IPAC’11, San Sebastian, Spain, 2011;
- S. Belomestnykh et.al., *SRF and RF systems for CeC PoP experiment*, NA-PAC’13 Pasadena, CA, 2013;
- I. Pinayev et.al., *First results of the SRF gun test for CeC PoP*, IPAC’16, Busan, Korea, 2016;
- I. Pinayev et.al., *Commissioning of the CeC PoP accelerator*, NAPAC’16, Chicago, IL, 2016;
- S. Belomestnykh et.al., *Commissioning of the 112 MHz SRF gun*, SRF2015, Canada, 2015;
- I. Pinayev et.al., *Performance of CeC PoP Gun During Commissioning*, NAPAC’16, Chicago, IL, 2016;
Back-up Stalk

Stainless Steel tubes plated with 25 microns of copper and 1 micron of gold

2" Stalk tube section

3" Stalk tube section

Spider to affix the stalk snout in the 112 MHz cavity
\[ P_{\text{Rad}} = \frac{1}{4} \left( \mu_0 H^2 - \varepsilon_0 E^2 \right) \]