Abstract

For the funded BERLinPro project, a 100 mA CW-driven SRF energy recovery linac (ERL), a SRF photoinjector cavity has to be developed which delivers a small emittance, $1 \text{ mm*mr @ 77 pC}$, high brightness beam while accelerating a high average current within given high power limitations. To achieve these goals the injector is being developed in a three stage approach. In the current design step a cavity shape was developed which fulfills the beam dynamics requirements, implements a high quantum efficiency (QE) normal conducting photocathode with the HZDR choke and insert design and allows for beam studies at currents up to 4 mA. This paper will describe the RF design process, higher order mode studies and the final layout for the cavity production at JLab.

GUN 1, A FIRST STEP TOWARDS 100 MA

The BERLinPro ERL will be a prototype facility demonstrating energy recovery with a 100 mA beam at 50 MeV energy while preserving a normalized emittance of better than $1 \text{ mm mrad}$ at a pulse length of 2 ps [1]. This accelerator is based on superconducting RF accelerator technology operated in continuous wave mode (CW). This high brightness at high average current goal places stringent requirements on the performance of the SRF photoinjector cavity. Besides the combination of a cavity with good HOM damping capabilities and optimized to meet the BERLinPro beam dynamic requirements, a major issue of a high current ERLs is beam loss and halo formation by dark current. The injector cavity must therefore deliver low dark current levels, which is partially in contradiction to have a low work function cathode [2] and high launch fields during emission to counteract space charge driven beam expansion [3].

In order to address different challenges of SRF injector cavity design and operation, HZB has followed a three stage approach of different cavity systems:

1. **Gun0**: A fully SC system with a lead cathode arc deposited on the back wall allowing beam studies while avoiding the complicated insert of a high QE normal conducting (NC) cathode in a SC environment. Results are published in [4–8].

2. **Gun1, this paper**: A beam dynamic optimized design with an HZDR-style cathode insert system [9] allowing operation up to 4 mA. It should demonstrate BERLinPro bunch parameters, serve as a HOM study test system and allow the usage of a high QE NC cathode within a SC environment.

3. **Gun2**: Lessons learnt from the Gun1 design will be implemented, it will feature two modified KEK c-ERL high power coupler [10] to allow 100 mA average current operation.

RF design and ancillary equipment

An overview of the cavity and helium vessel is given in Figure 1. It shows the cavity with the choke cell and cathode insert followed by the enlarged beam tube, allowing HOM propagation to the absorber following downstream the coupler port and SC solenoid. The cavity will be equipped with a blade tuner, featuring a stepper motor for coarse and piezos for fine tuning. For operation up to 4 mA beam current, the cavity will be powered by two CW-modified TTF-III couplers [11], allowing 10 kW power each. The stiffening ring position was optimized to have low helium pressure sensitivity, see [12].

Figure 2 depicts the setup of the injector cavity for RF simulations using Superfish [13] for RF optimization and CST MWS [14] to study non-symmetric effects as e.g. coupler kicks. The RF cavity design was driven by the aim to allow a beam extraction at a high local field on the cathode during the laser pulse while the beam energy is fixed to 2.6 MeV. Achieving high field components at the cathode by RF design is not sufficient. These calculations needed to be accompanied by particle tracking to consider transit time effects. A particle tracker and an automated Superfish call was implemented in a Matlab program to use...
optimization schemes for achieving high emission phases of the RF field for maximum kinetic energy at a given RF power constraint. This resulted in a 1.4 cell design, as described in [15].

**Field distribution**

Figure 3 shows the longitudinal and transverse electric field components versus $z$ for different cathode positions relative to the backwall.

![Figure 3: Longitudinal electric field component at $r=0$ and radial electric field at $r=1\text{mm}$ versus $z$ for different cathode positions.](image)

Table 1 summarizes the RF and operational properties of the cavity as expected by the simulations. The calculated dependance of beam energy with respect to launch phase and maximum on-axis field $E_0$ was bench-marked by measurements with gun0 [5], [7]. The field distribution was optimized such, that there is maximum on-axis field as close as possible to the cathode, but not on the cathode itself. This helps to minimize the danger of field emission (FE) and results in radial field components for initial focussing. Due to manipulation of the arc shape merging the skew back wall with the cathode opening, the electric peak field was moved from there to the center iris (Figure 4).

Table 1: Cavity figures of merit for the TM010-π mode of injector cavity1 at $E_0=30\text{ MV/m}$ and cathode retracted from 0-2.5mm. Note, that $Q_{ext}$ is optimized for 4 mA beam current.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cavity 1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R/Q(\Omega)$</td>
<td>150-149.5</td>
</tr>
<tr>
<td>$E_{\text{peak}}/E_0$</td>
<td>1.5-1.45</td>
</tr>
<tr>
<td>$E_{\text{cathode}}/E_0$</td>
<td>1.0-0.58</td>
</tr>
<tr>
<td>$H_{\text{peak}}/E_{\text{peak}}(\text{mT}/(\text{MV/m}))$</td>
<td>2.2</td>
</tr>
<tr>
<td>$\Phi_{\text{launch}}(E_{\text{kin,max}})\text{ (deg.)}$</td>
<td>60-50</td>
</tr>
<tr>
<td>$E_{\text{launch}}\text{ (MV/m)}$</td>
<td>26-13.3</td>
</tr>
<tr>
<td>$E_{\text{kin}}\text{ (MeV)}$</td>
<td>2.6</td>
</tr>
<tr>
<td>$k_{cc}\text{ (%)}$</td>
<td>1.6</td>
</tr>
<tr>
<td>$Q_{ext}^3$</td>
<td>$3.6 \cdot 10^6$</td>
</tr>
<tr>
<td>$f_{1/2}(\text{Hz})$</td>
<td>185</td>
</tr>
<tr>
<td>$P_{\text{forward}}\text{ (kW)}$</td>
<td>8.4</td>
</tr>
<tr>
<td>$\Delta f_{\text{peak}}\text{ (Hz)}$</td>
<td>20 (expected)</td>
</tr>
</tbody>
</table>

The latter being a position where FE current less probably leaves the structure with the beam. Figure 5 shows gained kinetic energy versus emission phase for $E_0=30\text{ MV/m}$ using the tracking code and CST’s PIC solver for 1.5mm cathode position. A maximum is at 55 degrees with 2.6 MeV. Dark current emitted around 90 degrees phase, most probably from or next to the cathode will leave the structure with 1.5-2.4 MeV.

Retraction of the cathode allows for stronger RF focussing of the beam during extraction by the laser pulse, but leads to a slight decrease of the normalized shunt impedance $R/Q$ from 150 to 149.5 $\Omega$ and further decreases the ratio cathode field to maximum on-axis field from about 1 to 0.58. The launch phase for maximum energy gain is

![Figure 4: Surface electric and magnetic field of the gun cavity including cathode stock and choke cell normalized to maximum on-axis field $E_0$ of 30 MV/m versus surface path length $s$ starting from the cathode, through the Petrov/choke filter part and finally the cell surfaces.](image)
shifted by 10 degrees from 60 at zero position to 50 at the 2.5 mm position. This reduces the effective launch field by 49%, but the dark current emitted from the cathode by about a factor of eight according to the Fowler-Nordheim ($\beta_{FN}=1$) equation. Nevertheless, as depicted in Figure 6, whereas in this design the beam tube was chosen such to theoretically propagate all HOMs, studies with this cavity will show, whether a reduction of the beam tube is possible for future designs, allowing more efficient solenoid designs.

Figure 5: Comparison of kinetic energy versus emission phase at $E_0=30$ MV/m for several bunches (blue) using a simple tracking program compared to CST’s PIC Solver. The black lines denote a possible phase and resulting energy range of field emitted dark current near the cathode.

shifting the cathode too much leads to an overlap of the choke and $\pi$-mode frequency. Thus tuning of the choke cell is mandatory in order to avoid high losses, discharges or multipacting in the cathode insert section.

Figure 6: $D(k^2)$ function of Superfish showing the TM$_{010}$ monopole passband and the resonance of the choke structure, which varies with the cathode position. At -2.6 mm position the $\pi$-mode and choke mode overlap.

OUTLOOK

The design for this cavity is finished and the construction of the cryo-module is being finalized. Currently the first dies for the half cell manufacturing are produced at JLab, so that the first vertical RF tests may be expected for this summer. In the meantime studies for the high power injector cavity have started.

REFERENCES

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