High gradient ultra-high brightness C-band photoinjector:

BD results and comparison for different cathode peak fields

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Introduction

• The photoinjector is a key device to reach the high brightness \( B = \frac{2I}{\epsilon_f^2} \).

• The first contribution to the beam emittance is the thermal one \( \epsilon_{th} \), while to reduce the emittance growth due to space charge forces, after the emission an RF structure pushes quickly the beam up to relativistic energy.

• To reduce the beam emittance some efforts are done increasing the cathode peak field, reducing the laser spot on the cathode \(^1\) and pushing the beam faster up to relativistic energies. \(^2,3\)

\[
\epsilon_{th} \propto \sigma_x \\
\epsilon_{sc} \propto \frac{1}{E_{\text{cath}}}
\]

• Maintaining the same \( f_{RF} \), the same RF structure lenght and increasing the peak field, the disadvantage could be an higher energy at the entrance of the first accelerating structure. In that case an RF compression is not possible.

1. Rosenzweig, J.B., Colby, E. TESLA-95-04.
In order to maintain the main features of the well established S-band working points, a 1.6 cells C-Band gun was used with 240 MV/m. In this way $E_{final} \approx 6 \text{ MeV}$ as in the S-band 120 MV/m case.

Each device length was scaled by a factor 2 and each field was doubled respect to the S-Band scenario.
The design and fabrication of the new gun will be driven by the same criteria used in the design of high gradient X band structures developed in the framework of linear collider projects (NLC, JLC and CLIC). There are four main quantities that play a crucial role in the BDR control: the peak electric field, the modified Poynting vector ($S_c$), the RF pulse length ($t_p$) and the pulsed heating ($\Delta T$). The gun will be designed and fabricated keeping under control these quantities.


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{cath}}$</td>
<td>240 MV/m</td>
</tr>
<tr>
<td>$\Delta f_{0-\pi}$</td>
<td>$\approx$ 100 MHz</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>11000</td>
</tr>
<tr>
<td>$\beta$</td>
<td>3</td>
</tr>
<tr>
<td>$P_{\text{diss}}@240\text{MV/m}$</td>
<td>12 MW</td>
</tr>
<tr>
<td>$E_{\text{CAT}}/\sqrt{P_{\text{diss}}}$</td>
<td>67 [MV/mMW$^{0.5}$]</td>
</tr>
<tr>
<td>$P_{\text{in}}@240\text{MV/m}$</td>
<td>31 MW</td>
</tr>
<tr>
<td>$\Delta T @ 200$ ns</td>
<td>$&lt;30 , ^\circ\text{C}$</td>
</tr>
<tr>
<td>RF pulse length</td>
<td>$&lt;200$ ns</td>
</tr>
<tr>
<td>Av diss power</td>
<td>2000-200 W</td>
</tr>
<tr>
<td>Rep. Rate</td>
<td>1000-100 Hz</td>
</tr>
</tbody>
</table>

M. Croia
During the RF compression solenoids on the first two sections are used to keep under control the beam spot size and the emittance.

- **C-BAND SECTIONS** \((l = 2m)\) operating at 40 MV/m average accelerating gradient (as example, PSI-like structures with 1 klystron every 2 sections)

- Using the GPT code the section positions and the integrated magnetic fields were optimized. The first section RF phase was setted to perform an RF compression (velocity bunching).
- **Q = 75 pC**

- **GPT 500k particles**

- Laser on cathode: 
  \[
  \begin{align*}
  \text{radius} &= 294 \, \mu m \text{ (uniform)} \\
  E &= 4.66 \, eV \text{ (corresponding to } \lambda = 266.7 \, nm) 
  \end{align*}
  \]

- The field on the cathode is: 
  \[
  E_z = E_0 \sin \phi_{\text{launch}}.
  \]
  In this case
  \[
  E_0 = 240 \, MV/m \quad \text{and} \quad \phi_{\text{launch}} = 35^\circ \quad \rightarrow \quad E_z \approx 137 \, MV/m
  \]

- The starting intrinsic emittance was analytically recalculated for an ideal high gradient case and setted to: 
  \[
  \varepsilon_{\text{int}} = 118 \, nm.
  \]
Main beam parameters trend

\( \sigma_{n,\text{rms,final}} \approx 0.15 \, \mu m \)

\( E_{\text{gun,exit}} \approx 6 \, \text{MeV} \)

\( E_{\text{final}} \approx 165 \, \text{MeV} \)

\( E_{\text{spread}} \approx 0.06 \, \% \)
"Rolling" slice analysis

$L_{slice} = 30 \mu m$

$I_{slice} \approx 25 A$

$\sigma_{z,\text{final}} \approx 296 \mu m$

Courtesy of A.R.Rossi and S. Romeo
SOFT RF COMPRESSION FOR COMPACT LIGHT [1]

2. Compact Light, [www.compactlight.eu](http://www.compactlight.eu)
Spot and emittance

\[ \epsilon_{r,\text{final}} \approx 0.15 \, \mu m \]

\[ \sigma_r \approx 60 \, \mu m \]

\[ E_{\text{final}} \approx 108 \, \text{MeV} \]

\[ E_{\text{spread}} \approx 1.4\% \]
Beam compression and slice analysis

\[ \sigma_{z,\text{final}} \approx 105 \, \mu m \]

\[ L_{\text{slice}} = 15 \, \mu m \]

Compression factor \( \approx 3 \)
## FINAL PHOTO-INJECTOR PARAMETERS

<table>
<thead>
<tr>
<th>units</th>
<th>ON CREST</th>
<th>SOFT RF COMPRESSION</th>
<th>COMPACT LIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>pC</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>E</td>
<td>MeV</td>
<td>165</td>
<td>107</td>
</tr>
<tr>
<td>$\sigma_E/E$</td>
<td>%</td>
<td>0.06</td>
<td>1.4</td>
</tr>
<tr>
<td>$\varepsilon_{n,rms}$</td>
<td>$\mu$m</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>$\mu$m</td>
<td>296</td>
<td>105</td>
</tr>
<tr>
<td>$I_{peak}$</td>
<td>$A$</td>
<td>22 (25slice)</td>
<td>62 (80 slice)</td>
</tr>
</tbody>
</table>
Comparison for different cathode peak fields

• To explore beam final parameters for lower gradients we optimized different layouts decreasing the cathode peak field.

• The scan was performed re-optimizing the entire line (magnetic fields, launch phases and structure positions).

\[ E_{cath}[240, 220, 160, 130] \frac{MV}{m} \]

Laser on cathode dimensions and intrinsic emittance are properly scaled for each case

Re-optimized magnetic field for each case

Beams are on crest and solenoids around sections are switched OFF

• This study can be useful in the case we will reduce the cathode peak field (160 MV/m), to increase the bunch repetition rate toward the KHz.
\( \varepsilon_{n,\text{rms,final}} \approx 0.15 \mu m \)
\( \sigma_{t,\text{gun_exit}} \approx 0.99 \text{ ps} \)
\( E_{\text{spread}} \approx 0.06 \% \)

\( \varepsilon_{n,\text{rms,final}} \approx 0.15 \mu m \)
\( \sigma_{t,\text{gun_exit}} \approx 1.05 \text{ ps} \)
\( E_{\text{spread}} \approx 0.07 \% \)
\( \varepsilon_{n,\text{rms,final}} \approx 0.18 \, \mu m \)

\( \sigma_{t,\text{gun exit}} \approx 1.28 \, ps \)

\( E_{\text{spread}} \approx 0.1 \% \)

\( \varepsilon_{n,\text{rms,final}} \approx 0.32 \, nm \)

\( \sigma_{t,\text{gun exit}} \approx 1.39 \, ps \)

\( E_{\text{spread}} \approx 0.12 \% \)
Comparison for different cases (ON CREST)

Using 160MV/m it is possible to improve the beam Brightness and increase the repetition rate toward kHz.
CONCLUSIONS

- We started to study and simulate an ultra-high gradient C-band photoinjector. An ultrafast RF approach and a preliminary new design of the cells was made.

- This device was optimized also to guide the X-band linac for the COMPACT LIGHT design study, and the simulation results completely match the requests.

- It can represents also a good option for EUPRAXIA.

- To increase the repetition rate we explored which gradient improve the beam brightness compared to an S-band gun (110 MV/m). A gradient of 160 MV/M seems to be a good compromise.

- A lot of work needs to be done: RF tests, dark current, proper cathode material...