DESIGN MODELLING OF RF INJECTOR FOR ICS GAMMA-RAY SOURCE SYSTEM

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Abstract

High brightness beams are desired for application to Inverse Compton Scattering (ICS) systems for generation of high-quality x- and γ-rays. In the ICS mechanism high energy electron is interacting with photon. It results in scattered photon with high energy. Computer simulations of electron beam in the rf injector for ICS γ-rays source were carried out and results are presented. Different configurations of injector model were analysed.

INTRODUCTION

The development of high energetic photon sources based on the ICS is currently in progress [1, 2]. The ICS gamma-ray sources find applications in medicine, industry, nuclear waste treatment, and fundamental research in nuclear photonics, photo-fission, and astrophysics [3-5]. The advanced Variable Energy Gamma System (VEGA) is under implementation at the ELI-NP, as one of the major components of the infrastructure developed in Bucharest-Magurele, Romania [6]. The extreme γ beams will be dedicated for nuclear physics and nuclear photonics experiments for worldwide users. The VEGA system consists of an RF injector, LINAC, storage ring, and advanced optical cavity where interaction point is located.

This paper focuses on the rf injector. The aim is to investigate different configurations of the injector to find the optimal electron beam performance for further acceleration in the Linac [7]. Considering the specification of the Linac, injector’s parameter targets are as listed in Table 1.

Table 1: Injector System Specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy gain</td>
<td>&gt; 10 MeV</td>
</tr>
<tr>
<td>Trans. core emittance (95%)</td>
<td>&lt; 5 π mrad mm</td>
</tr>
<tr>
<td>RMS energy spread</td>
<td>&lt; 110 keV</td>
</tr>
<tr>
<td>Bunch length</td>
<td>&lt; 1 mm</td>
</tr>
</tbody>
</table>

The rf injector is modelled with use of ASTRA [8], computer software package used for modelling, computing and simulating charged particle beam in the accelerator system. This includes, in computation, the space-charge effect that dominates in non-relativistic beams. The initial setup presents Table 2.

Table 2: Initial Beam Setup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of particles</td>
<td>40 000</td>
</tr>
<tr>
<td>Total charge of particles</td>
<td>1 nC</td>
</tr>
<tr>
<td>Trans. particle distribution</td>
<td>truncated gaussian</td>
</tr>
<tr>
<td>RMS bunch size, σ_x, σ_y</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>Long. particle distribution</td>
<td>plateau</td>
</tr>
<tr>
<td>RMS value of emission time</td>
<td>5 ps</td>
</tr>
</tbody>
</table>

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SYSTEM CONFIGURATION

The system was simulated in two major configurations, illustrated in Fig. 1. The first considers an RF gun, and solenoid magnets in different arrangements. The second includes a standing wave (SW) cavity. The RF gun is a 1.6 cell structure. The operating frequency of the rf injector was set to 2.856 GHz, the electric field gradient at the cathode 120 MV/m, and the input phase 0°. The 11 cells SW cavity operates with max field gradient 28 MV/m.

![Figure 1: Different configuration of RF injector. Position for output generation is 0.4 m and 1.1 m.](image)

RESULTS OF COMPUTER SIMULATIONS

Firstly, the RF gun with the single solenoid, and then with two solenoids, arranged as the Helmholtz Coil (HC), were investigated. The position of the solenoid versus cathode was varied. The analysis of the transverse emittance and transverse spot size of the beam were done for different magnetic field amplitudes. As it is presented in Fig. 2, the best emittance is obtained when the solenoid magnet is at the distance between 0.14 and 0.15 m from the cathode, and the magnetic field is set to 0.36 T.

![Figure 2: Transverse core emittance (95% particles) and beam spot vs. solenoid position and field amplitude.](image)

In the next step the HC was implemented. The position versus the cathode and the field amplitude of the solenoids were varied. The emittance (Fig. 3) decreases with distance from the cathode, and reaching minimum it starts increasing. Such an effect is expected, the higher amplitude fields result in an over focusing of the beam and the emittance is increasing when the field increases.
Secondly, the SW cavity was added for investigation. Two different arrangements of solenoid magnets were simulated. The first arrangement includes only one solenoid, located at the distance 0.14 m from the cathode. The solenoid field amplitude was set to 0.42 T. The second arrangement includes three solenoids, the one at the distance 0.14 m and with field amplitude 0.42 T, and two other solenoids are set in the HC configuration. The magnetic field amplitude at each HC solenoid was set to 0.24 T. The distance from the cathode and electric field input phase were varied.

The analysis of the system with one solenoid delivered the results, the emittance reaches the optimum (3.5 \( \pi \) mrad mm) at the distance 0.4 m between the SW cavity and the cathode, and at the input phase between -50\(^\circ\) and -60\(^\circ\). The average beam energy is increasing with the increase of the phase at the SW cavity touching the maximum at 0\(^\circ\) with the value of 14 MeV. The bunch length also depends on the input phase of the electric field at the SW cavity. The bunch length is shortest at -120\(^\circ\), and reaches 0.1 mm. The bunch shortening occurs at the expense of the energy gain. The highest energy gain is received when the shortening of the bunch is avoided. The phase can be chosen so that both the bunch shortening and the energy gain can be obtained.

Another arrangement with three solenoids was investigated for different input phase of electric field at the SW cavity, between -130\(^\circ\) and 40. Figure 4 presents the transverse emittance versus the HC location, for the input phase 0\(^\circ\) and -120\(^\circ\). The 0\(^\circ\), where the gain in the beam energy is the biggest but no happen longitudinal bunch compression, and -120\(^\circ\), where the bunch compression is the strongest, but the beam gains no energy after passing the SW cavity. The settings of the first solenoid stay the same, i.e., 0.14 m and 0.42T. The magnetic field amplitude at each solenoid in the HC was set to 0.24 T, and the distance between two solenoids is 0.088 m. The SW cavity was located at 0.4 m from the cathode.

The received results are as expected. It occurs, at 0\(^\circ\), significant gain in the beam energy (Fig. 5). The higher energy means the beam is more rigid, i.e., it is harder to treat it with the magnetic field and there is no significant improvement in emittance (Fig. 6 left). The beam with lower energy is less rigid and more influenced by the magnetic field from the solenoids. There is effect on the beam emittance (Fig. 6 right).

The compromise to have the beam compressed and not yet decelerated is setting -95\(^\circ\) phase of the electric field. Figure 7 presents the results for the beam energy gain and the emittance. The emittance is improved from 4.1 up to 2.9 \( \pi \) mrad mm.

Figure 4: Transverse core emittance (95%) versus HC position; phase 0\(^\circ\) (left) and -120\(^\circ\) (right).

Figure 5: Beam energy gain along injector at 0\(^\circ\) (left) and -120\(^\circ\) (right) phase at SW cavity (HC located at 0.55 m).

Figure 6: Transverse emittance along injector at 0\(^\circ\) (left) and -120\(^\circ\) (right) phase at SW cavity (HC at 0.55 m).

Figure 7: Beam energy gain (left) and transverse emittance (right) along injector at -95\(^\circ\).

Figure 8 depicts the result of the beam emittance, and the beam spot size, versus HC magnetic field amplitude. The magnetic field value presented on the horizontal axis is the field at both solenoids separately (resultant field is stronger accordingly).

Figure 8: Transverse core emittance (left) and Transverse beam spot size (right) versus HC magnetic field, Phi=0\(^\circ\).
Figure 9 presents the rms beam energy spread along the RF injector.

Figure 9: RMS energy spread along RF injector, Phi=0°.

CONCLUSION

The analysis of different configurations of the RF injector system were performed. The electron beam is created and the bunch is initially formed in the RF gun cavity. The solenoid magnets confine the beam near the axis, reducing the energy spread that occurs by the space charge effect, and the SW cavity affects the beam energy, bunch length and energy spread. The computer simulations were run with different settings of the components’ parameters – the input phase of the electric field, the strength of the magnetic field. The different locations of the components versus the cathode were investigated. First, the RF injector was examined in configuration with only one solenoid located at the exit of the gun cavity and with two solenoids arranged for the HC. The HC creates nearly uniform magnetic field at the centre, the field might be treated as a constant parameter for the analysis. Nevertheless, the fringe fields cannot be neglected. Also, the investigation with the SW cavity was made, in the configuration with one solenoid and three solenoids.

In the configuration with one solenoid, the emittance increases with the increase of the distance between SW cavity and the cathode, touching the lowest value at 0.4 m. The same, the spot size is minimal there. The beam parameters were investigated, at that position, versus the input phase of the SW cavity electric field. The lowest emittance was achieved for the phases between -50° and -60°, and the lowest beam spot was achieved for the phases between -30° and 20°. The average beam energy versus the input phase was examined and the highest value was achieved for the phase of 0°. The bunch can be compressed with negative phase at the SW cavity, and the shortest bunch length was received at -120°. The bunch compression occurs at the expense of the energy gain. What is more, at the -120° the beam experiences deceleration. In the configuration with the three solenoids the beam parameters were analysed versus the input phase of the SW cavity electric field.

The optimal components’ location and rf injector configuration are presented in Fig. 10. Table 3 summarizes the “optimal” components’ settings based on the presented results, and the Table 4 presents the obtained parameters.

Figure 10: Optimal configuration of RF injector.

<table>
<thead>
<tr>
<th>Parameter RF gun SW Cav.</th>
</tr>
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<tbody>
<tr>
<td>E-field gradient (max) [MV/m]</td>
</tr>
<tr>
<td>Input phase [°]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter Solenoid HC</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-field (max) [T]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter Specified Simulated</th>
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<tbody>
<tr>
<td>Beam energy gain [MeV]</td>
</tr>
<tr>
<td>Emittance $\varepsilon_{xy}$ [π mrad mm]</td>
</tr>
<tr>
<td>Energy spread rms [keV]</td>
</tr>
<tr>
<td>Bunch length [mm]</td>
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REFERENCES


