BEAM PHASE-SPACE STUDY FOR AREAL RF PHOTOGUN LINAC*

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Abstract

In order to produce high brightness electron beams with sub-picosecond bunch duration, the creation of Advanced Research Electron Accelerator Laboratory (AREAL) at CANDLE based on photocathode RF gun is under consideration. For several experimental setup purposes the linac will operate in single and multibunch modes with final beam energy 5-20 MeV and the bunch charge 10 –100 pC. The study of beam phase space evolution along the linac is performed to optimize the beam main characteristics: emittance, bunch length and energy spread. The dependence of longitudinal and transverse distribution of electrons in photocathode region on RF cavity performances is analyzed.

INTRODUCTION

The laser driven photocathode RF electron guns are under intensive study in number of laboratories [1-3] due to their high potential for obtaining the ultra-shot high brightness electron beams. The ultra-low emittance electron beam in laser driven RF electron guns is realized due to high acceleration field of RF cavity that prevents the emittance growth caused the space charge effects in cathode region. The bunch duration is controlled by the pulse width of the laser field thus the bunching section is not necessary. The synchronization is easily achieved with laser pulse adjustment.

The basic aim of the AREAL photocathode RF gun linear accelerator [4] is the generation of 5-20 MeV energy, small emittance and ultrashort duration electron bunches for advanced research in the fields of accelerator and beam physics and potential application for electron diffraction experiments [5].

The main design of the AREAL facility is composed of laser driven S-Band RF gun, 1m long two S-Band accelerating sections and dispersive section for energy spectrum measurements. The energy gain along the linac is planed 4.7 MeV from the gun, about 4 MeV from the first accelerating structure, and 12 MeV from the second structure.

PHILOSOPHY AND MODEL

The space charge dominated single bunch phase space study along the accelerator is the primary approach to optimize the design parameters of the facility. The schematic layout of the AREAL facility is presented in Fig. 1. The main design parameters of the electron beam are given in Table 1. The tracking simulations have been performed along the accelerator using ASTRA code [6]. The simulations are aim for optimization of the facility layout and the RF parameters supplying S-band gun cavity and the two accelerating sections.

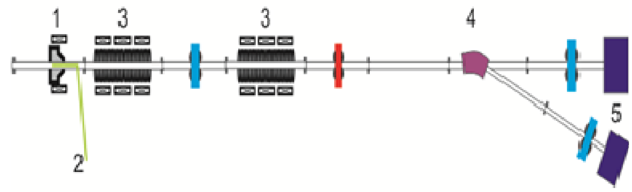

Figure 1: Schematic layout of AREAL 20 MeV S-Band linear accelerator. 1- RF –photo gun, 2- laser, 3- S-Band accel. sections, 4 –spectrometer, 5 - Beam dump.

Table 1: Beam Parameters List

Main Parameters	Single bunch	Multibunch
Beam energy	5-20 MeV	5-20 MeV
Bunch Charge	100 pC	5-10 pC
Transv. norm emit.	<0.3 mm-mrad	<0.3 mm-mrad
Rms bunch length	<0.8 mm	<0.8 mm
Transv. rms beamsize	1 mm	1 mm
rms energy spread	<20 keV	<20 keV
Bunches per RF pulse	1	50
RF pulse length	1μs	1μs
Pulse repetition rate	1 Hz	1Hz

For single bunch operation mode the space charge effects are major due to small rms bunch sizes in transverse (< 2mm) and longitudinal (< 1 mm) directions so the main subject of optimizations is the gun section. The rest of accelerator is tracked to obtain optimal parameters setup for RF phase and gradient in both structures to obtain the minimum transverse normalized emittance in compromise of the available minimal rms energy spread. To compensate the transverse beam blow due to space charge effects the solenoid magnet focusing is used starting from photocathode.

One of the main criteria of the parameters optimization is the beam laminar flow preservation, i.e. keeping beam divergence low and constant along the beam path. As initial bunch profile 10000 macroparticles with total charge of 100 pC and 5 ps rms bunch length at the cathode were generated, with transverse Gaussian and longitudinally uniform particle distributions within the bunch. The electric and magnetic field profiles were transformed from the existing data. Existing data of gun electric field profile was scaled to 1.6 cells, and the

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solenoid magnet length was scaled from 30 to 15 cm. The number of cells for travelling wave accelerating section is 24 including two coupler cells.

For simulations the following philosophy is kept:

- The optimum gun RF phase and gradient for the best capture of emitted electrons with the minimal energy spread at the entrance of the first accelerating structure.
- The optimum magnetic field of solenoid to get smooth focusing
- The minimum of the energy spread at the end of linac by tuning RF phase of accelerating structures.
- The minimum transverse normalized emittance along the linac.

The bunch length of 5 ps is about 12 degree of 3GHz RF phase, thus smaller gradient and off-crest RF phase of the first accelerating structure is considered to preserve the linear rotation of longitudinal phase space.

SIMULATION RESULTS

For the preliminary design of the AREAL facility numerous simulations have been performed to optimize the RF parameters at the gun and accelerating sections. The RF parameters have been optimized for the facility single bunch operation mode from the optimal beam emittance and energy spread points of view.

The gun gradient scan was performed to get the minimum transverse emittance and energy spread at the gun exit. The results of the simulations for the electron beam transverse emittance at the gun exit versus the cavity RF gradient are presented in Fig. 2. The optimum with the space charge effects is achieved for the RF gradient of about 80-90 MV/m.

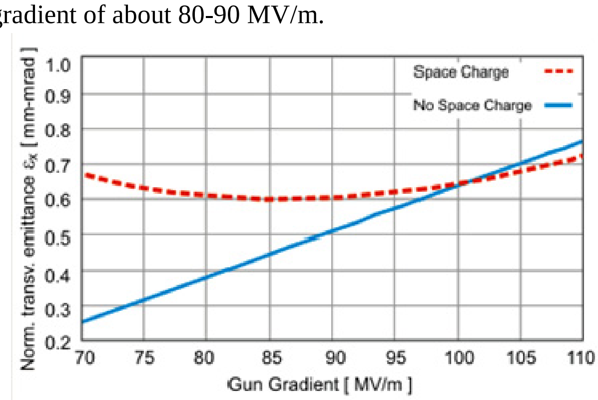

Figure 2: Transverse emittance at the gun exit versus the acceleration gradient in RF cavity. The results with (red) and without (blue) space charge effects are shown.

Figure 3 shows the beam rms energy spread versus RF gradient at the gun exit. With the space charge effects the minimum rms energy spread is achieved for the acceleration gradient of about 90 MV/m. Thus the optimal gradient of 90MV/m in RF cavity is foreseen to obtain the minimum normalized beam emittance and the minimum rms energy spread.

The impact of space charge forces on transverse emittance and energy spread is studied by comparing simulation results with and without space charge effects (Figs. 2, 3).

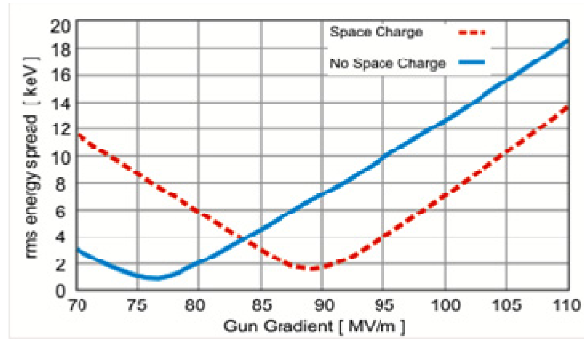

Figure 3: The beam RMS energy spread at the gun exit versus acceleration gradient. The results with (red) and without (blue) space charge effects are shown.

The simulations were performed to obtain the minimum emittance and energy spread at the position of 0.25 cm from photocathode (the location of gun exit flange) by scanning the RF acceleration field phase. The RF phase scan is performed with and without magnetic field of the main focusing solenoid. The dependences of the beam normalized emittance and rms energy spread versus gun RF phase are presented in Fig. 4. The optimal operating RF phase for gun is chosen 32 degree which is a compromise of the minimum emittance and energy spread at the RF gun exit.

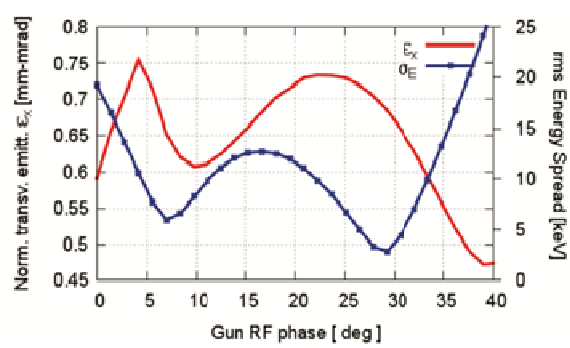

Figure 4: Gun RF phase scan. Normalized emittance and rms energy spread at 0.25m from photocathode.

For the single bunch rms energy spread in tracking calculations both correlated and uncorrelated contributions are taken into account. Since the dispersive bunch compression is not foreseen in the design the uncorrelated energy spread contribution will decrease with increasing the beam energy. The correlated energy spread induced due to RF voltage and wakefields in accelerating sections has been optimized by off-crest particle acceleration. The gun focusing solenoid magnet is adjusted to have laminar beam flow, i.e. smooth focusing. For that value of solenoid magnetic field the optimal position for the first accelerating section is the beam size waist position obtained at 1.85 m far from photocathode. The accelerating gradient and phase of the first accelerating section are optimized to obtain the minimum energy spread and transverse emittance at the entrance of the second accelerating section at 4.0 m from cathode. The transverse phase space profiles at the gun exit, the entrance and exit of the first and the second accelerating sections are given in Fig. 5.

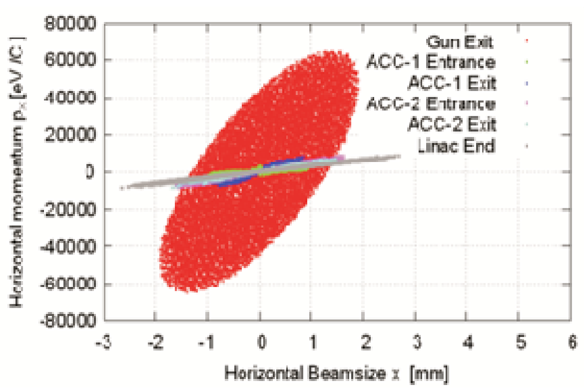

Figure 5: Transverse phase space profiles at the gun exit, entrance and exit of the first and the second accelerating sections.

The longitudinal phase space profiles at the gun exit, the entrance and exit of the first and the second accelerating sections are given in Fig. 6. For longitudinal phase space the minimization of correlated energy spread is performed by tuning the RF phases and gradients in both accelerating structures.

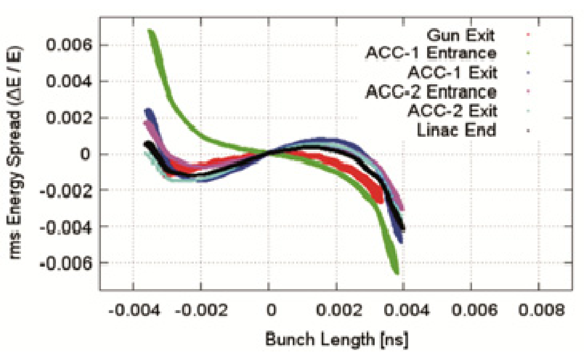

Figure 6: The longitudinal phase space profiles at the gun exit, entrance and exit of the first and the second accelerating sections.

For the first accelerating structure following the RF gun the optimal maximum accelerating gradient is obtained around 13 MV/m. For the second accelerating section the optimum gradient is about 17 MV/m. The total maximum energy gain along the entire linac including the RF gun is about 23.5 MeV. For lower energy operation of the facility the optimization of the RF phases and gradients for both accelerating structures are foreseen.

Start-to-end simulation has been performed for the AREAL design with the optimal setup and RF parameters. The evolution of the beam normalized emittance, rms transverse size and the rms correlated energy spread along the entire facility is presented Fig. 7.

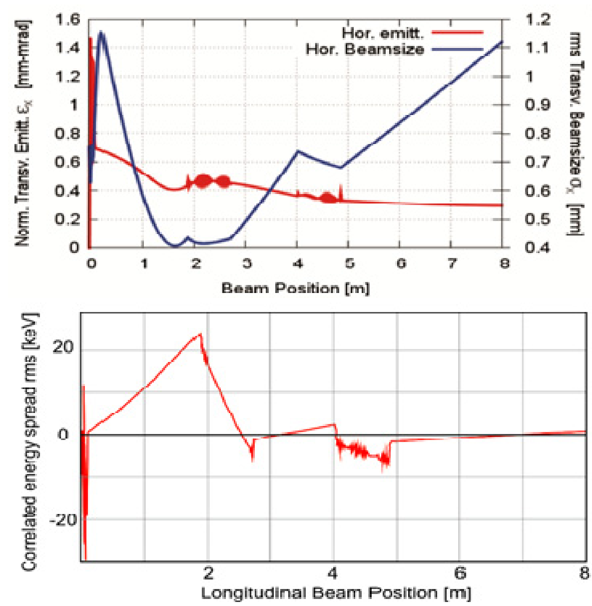

Figure 7: Transverse normalized emittance, beamsize (top) and correlated energy spread (bottom) evolution along the linac.

At the linac exit the maximum beam energy is about 23.5 MeV with the normalized transverse emittance of about 0.3 mm-mrad and the rms energy spread is below 0.1%. The minimum beam size is achieved in the first acceleration section, and further optimization of the beam optics is foreseen.

CONCLUSION

For the preliminary design of AREAL 20 MeV photocathode RF gun linear accelerator the simulations have been performed to optimize the beam rms energy spread and transverse normalized emittance. The minimum emittance and the rms energy spread at the end of linac are obtained using the present design performance of AREAL facility. The obtained results of space charge dominated bunch tracking simulations through the linac have shown the potential for further optimization. The work is in progress.

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