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MULTI-OBJECTIVE OPTIMIZATION OF AN SRF PHOTOINJECTOR WITH BOOSTER SECTION FOR HIGH BRIGHTNESS BEAM PERFORMANCE*

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Abstract

Several future accelerator projects, light sources and user experiments require high brightness electron beams. Superconducting radio frequency (SRF) photoinjectors operating in continuous-wave (cw) mode hold the potential to serve as an electron source generating beams of high peak brightness and short bunch lengths. Different operation and design parameters of the SRF photoinjector impact the beam dynamics and thus the beam brightness. An universal multi-objective optimization program based on a genetic algorithm was developed to extract optimum gun parameter settings from Pareto-optimum solutions. After getting the first optimum results, the photoinjector is supplemented with a booster section downstream. The new optimization results are presented. Further, the optimization program is applied to evaluate the impact of the field flatness of the gun cavity on the high brightness performance.

MOTIVATION

Relativistic, highly charged electron beams with compact phase spaces enable the operation of future accelerators and user experiments. High power FELs and energy recovery linacs (ERLs) as well as user experiments like ultrafast electron diffraction (UED) offer new research perspectives but have strong demands on the electron beam quality. The electron source of the accelerator plays an outstanding role in the setup since a high quality beam must already be generated and controlled at the source and it cannot be improved by beam manipulation downstream in the accelerator structure. SRF photoinjectors are able to operate such a facility as an electron source. Electrons are generated by photoemission at the cathode. Afterwards, the bunch is accelerated in a superconducting cavity to energies of several MeV using high gun gradients of several tens MV/m in cw mode. A solenoid magnet focuses the beam in the transverse plane and initiates transverse emittance compensation.

The 5D peak brightness B_{peak} represents a beam parameter that summarizes the quality of the transverse and longitudinal phase space. Depending on the bunch charge q_b, the beam brightness is inversely proportional to the transverse emittances ε_x, ε_y as well as the bunch length σ_t

$$B_{peak} \propto \frac{q_b}{\varepsilon_x \varepsilon_y \sigma_t} \quad (1)$$

Thus, in order to operate an SRF photoinjector and the downstream accelerator in a high brightness mode the transverse emittance and bunch length must be minimized simultaneously. The trade-off between these two parameters makes this task challenging. Furthermore, the emittance and bunch length depend, like the beam dynamics of the whole photoinjector, on the mentioned beam path elements (drive laser, gun and solenoid) and their corresponding settings. Space charge effects also play a major role in the non-relativistic regime of the gun. The task is to find a stable photoinjector setting for high brightness operation.

Therefore, a multi-objective optimization program based on a MOGA algorithm was developed [1]. The transverse emittance and bunch length represent the objectives in the optimization that have to be minimized depending on several decision variables presented by the photoinjector parameter settings. The optimization tool is able to select the best parameter sets for smallest transverse emittance and shortest bunch length values and thus, for a high brightness performance.

The developed Pareto optimization program is used to find stable settings to run the SRF photoinjector in a high brightness mode and to analyze the impact of the photoinjector parameters on the beam dynamics. Additionally, the physical limit of the analyzed photoinjector design is figured out. Up to now, the tool is successfully applied in the optimization of the electron source for bERLinPro, the ERL test facility planned for the next years at Helmholtz-Zentrum Berlin [1, 2, 3]. Figure 1 displays the Pareto optimum curve for the bERLinPro design case with one highlighted stable gun parameter set that fulfills the bERLinPro specifications. In a next step, it is tested if the program is able to optimize the complete injection line of an ERL and if the Pareto optimizer can be used for photoinjector design studies.

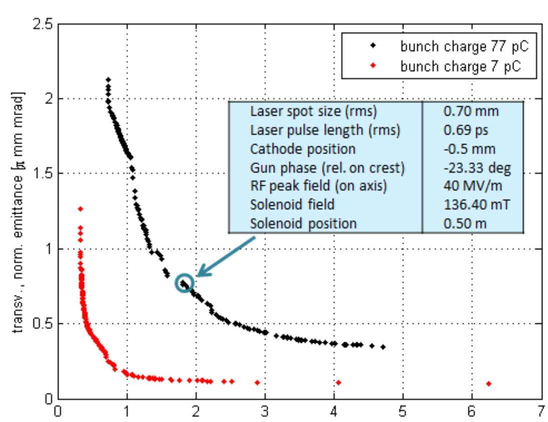

Figure1: Pareto optimum curves for 7 pC (diagnostic mode) and 77 pC (high average current mode) of the bERLinPro SRF photoinjector.

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ERL INJECTION LINE OPTIMIZATION

In order to accelerate the beam to higher energies and to suppress strong space charge (SC) effects, a booster section is added to the beam line behind the photoinjector in an ERL. The bERLinPro design suggests 3 2-cell booster cavities that will accelerate the beam to 6.5 MeV before it is merged to the main ERL recirculation ring. While the last 2 cavities operate on crest phase for maximum acceleration, the first one acts at zero crossing to achieve a longitudinal bunch compression by ballistic bunching. Table 1 summarizes the current bERLinPro booster settings.

Table 1: bERLinPro Booster Settings

Booster entrance position	3.2 m (from cathode)
Booster cavity 1 peak field	-4.8 MV/m
Booster cavity 1 phase	-90 ° (rel. on crest)
Booster cavity 2 peak field	-16.5 MV/m
Booster cavity 2 phase	0 ° (rel. on crest)
Booster cavity 3 peak field	-16.5 MV/m
Booster cavity 3 phase	0 ° (rel. on crest)

If the optimized photoinjector settings obtained with the Pareto optimizer are tracked through the bERLinPro booster, very promising results are achieved for photoinjector settings in the low emittance mode [$\varepsilon_{x,y} <$ 0.6 mm mrad in Fig. 1 at 77 pC]. The transverse emittance can be further decreased by RF focusing in the booster section while the bunch length is compressed by ballistic bunching. The concept fails at short bunch lengths $\sigma_z < 1.5$ ps already behind the photoinjector. Then, the booster further focuses the bunch in the longitudinal plane, but the transverse emittance grows due to SC effects. Therefore, the bunch length should not be intensively compressed in front of the booster. In order to obtain stable results in the short bunch length mode for the whole injection line, the optimization of the SRF photoinjector in the ERL application is extended by a booster section.

Seven new decision variables, the entrance position of the booster section, 3 cavity peak fields as well as 3 cavity phases, are added to the optimizer (bERLinPro design). The optimization point for smallest emittance and shortest bunch length values is set to 7 m behind the cathode. The Pareto optimum curve is again successfully figured out by the optimization program [see Fig. 2]. Compared to the optimum results of the photoinjector [see Fig. 1] the transverse emittance and bunch length can be significantly decreased by the booster section.

One photoinjector and booster setting at the required bERLinPro injector energy of 6.5 MeV is selected for a detailed analysis of the beam parameters (highlighted). The table in Fig. 2 represents the values of the decision variables of the corresponding parameter set. Figure 3 displays the evolution of the two objectives along the z-axis up to the optimization point for the highlighted example.

The transverse emittance is minimized by emittance compensation with the solenoid magnet in the photoinjector. The program moves the subsequent booster right before the emittance compensation point of the solenoid in order to maintain the minimum emittance through the booster. After a first emittance growth, emittance compensation starts in the last booster cavity due to RF focusing of the radial beam size. The emittance minimum in the optimization point at 7 m follows close to the focal point of the booster with smallest beam size.

After a moderate focusing due to the momentum chirping of the RF gun cavity field at -8.36° phase, the bunch length is strongly compressed by ballistic bunching in the 1st cavity. For that reason, the bunch is injected close to the zero crossing phase at -86.95°. The 2nd cavity provides on crest phase maximum acceleration but no further focusing. The bunch is still compressed but the slope is attenuated [see Fig. 3]. In order to hold this compression up to 7 m and to counteract the SC pressure arising from the transverse beam size focusing in the last 2 cells, an additional energy chirp for velocity bunching is imprinted on the bunch in the last booster cavity.

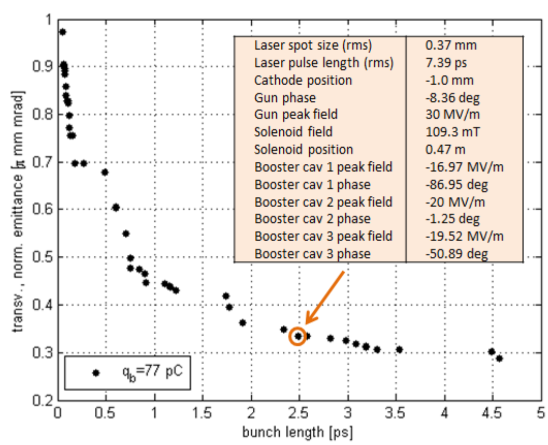

Figure 2: Pareto optimum settings for an SRF photoinjector followed by a 3 cavity booster section (bERLinPro design) for high brightness operation.

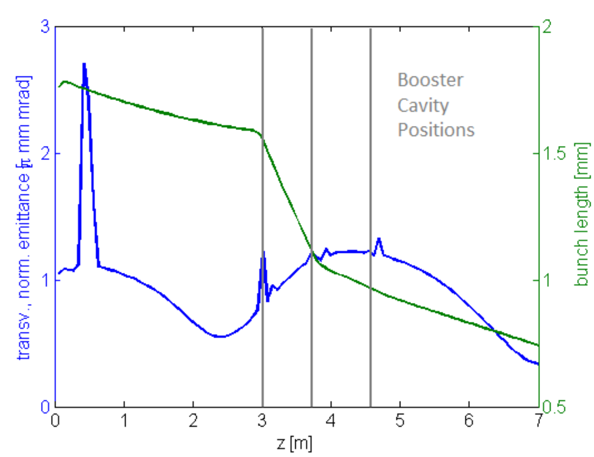

Figure 3: Evolution of the transverse emittance (blue) and bunch length (green) along the beam axis for the high-lighted setting in Fig. 2.

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FIELD FLATNESS OPTIMIZATION

In order to fully explore the possibilities of the presented Pareto optimizer a first design optimization was realized. Up to this point, the decision variables of the optimization are restricted to operation parameters that can be changed with less effort during the photoinjector and booster commissioning and run. Now, a first gun cavity design optimization is implemented considering the field flatness, thus the ratio of the peak field of the half-cell compared to the peak field in the full-cell of the gun cavity. Here, a field flatness value below 100% describes a field enhancement in the full-cell, while field flatness above 100% corresponds to higher fields in the half-cell compared to the full-cell. A balanced peak field (100% field flatness) between half- and full-cell is desired always.

The goal is to determine the impact of the cavity design on the transverse emittance and bunch length, and hence on the beam brightness. 8 different cavity fields from 59% up to 204% field flatness are observed. In order to compare the beams generated with different field flatness in the gun cavity, the final beam energy is set to 2.3 MeV (bERLinPro specification). The gun cavity gradients and injection phases are selected accordingly. The Pareto optimum fronts are evaluated at 2.5 m behind the cathode, thus the optimization is restricted to the SRF photoinjector without a booster section. The optimum results are plotted in Figure 4 with 100% field flatness displayed in the red curve and field enhancement in the full-cell (field flatness <100%). Figure 5 presents the Pareto fronts for field enhancement in the half-cell (field flatness >100%).

The bunch length can be significantly decreased towards higher field flatness, hence higher fields in the half-cell. The total momentum chirp of the cavity imprinted on the bunch is directly impacted by the field flatness. The momentum spread grows towards higher fields in the half-cell and thus higher field flatness values. This leads to stronger velocity bunching and shorter bunch lengths at the optimization point. The effect can be also observed in the Pareto optimum curves in Figs. 4 and 5. The field enhancement in the half-cell and cavity peak fields cause different acceleration voltages in the half cell that lead to different injection times of the bunch to the full-cell (phase slippage). In the case of a field flatness above 120% the corresponding total momentum chirp is not further increased but it converges at a field flatness of 150% and even decreases above. Therefore, the bunch length cannot further be compressed. The Pareto fronts start to move towards longer bunch lengths again (red curve in Fig. 5).

Additionally, a moderate improvement of the transverse emittance at higher fields in the half-cell can be observed. It can be traced back to stronger RF focusing by high radial electric fields at the photocathode. A cathode retreat of 1.5 mm supports this effect. Nevertheless, a stronger effect of the field flatness on the longitudinal phase space is detected.

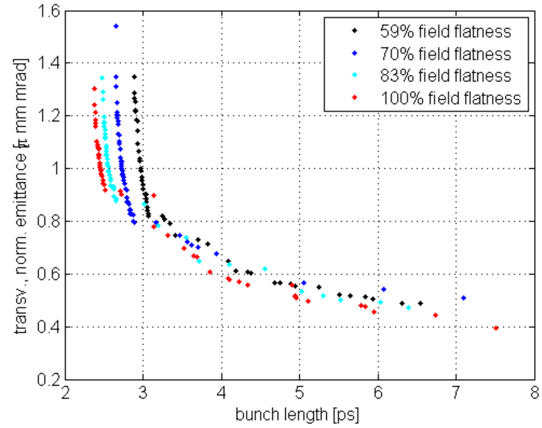

Figure 4: Pareto curves for 100% field flatness (red) and for field enhancement in the gun cavity full-cell.

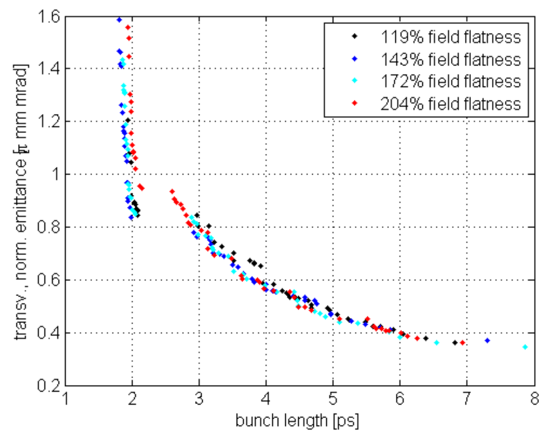

Figure 5: Pareto curves for field enhancement in the gun cavity half-cell.

SUMMARY & OUTLOOK

The presented program is able to optimize any RF photoinjector to operate it in a high brightness mode and to find its physical brightness limit. After being implemented to optimize photoinjectors for ERL and UED applications, this powerful tool is now extended to injection line and design studies.

A 3-cavity booster section is added to the ERL beam path. The Pareto optimizer is able to set the booster peak fields and phases to zero crossing and on crest acceleration in order to achieve minimum bunch length values, while focusing the bunch in the transverse plane. The results will support and facilitate the commissioning and operation of the booster module for bERLinPro. The optimization program will be deployed next for a design case study with 5 booster cavities in the injection line.

Furthermore, the Pareto optimizer was initially used for a cavity design study concerning the field flatness. The program proves that the bunch length can significantly decreased using a gun cavity field flatness above 100% with a field enhancement in the half-cell regarding that the field flatness does not exceed 150%. Nevertheless, a superconducting gun cavity with the desired 100% field flatness requires the smallest peak fields for high brightness operation at the selected energy.

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