MULTI-OBJECTIVE OPTIMIZATION OF AN SRF PHOTOINJECTOR FOR ERL AND UED APPLICATION*

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Abstract

Superconducting radio frequency (SRF) photoinjectors, running in continuous-wave (cw) mode, are able to generate electron beams of high average brightness and ultrashort bunches. Therefore, they satisfy the requirements of future accelerator facilities, such as energy recovery linacs (ERL). Further, SRF guns are able to provide relativistic probe beams for ultrafast electron diffraction (UED). Choosing suitable values for the drive laser, cavity and solenoid settings poses a great challenge for the injector commissioning and operation. Using multi-objective optimization based on an evolutionary algorithm, optimum gun parameter settings are extracted from Pareto-optimum solutions. The development of a universal multi-objective optimization algorithm for SRF photoinjectors as well as first Pareto-optimum results for an ERL and UED application of GunLab, the compact SRF gun test facility at Helmholtz-Zentrum Berlin, are presented.

MOTIVATION

The desire for high density relativistic electron beams pushes the development of future accelerators to the next level. High power FEL and ERL accelerators but also user experiments like UED offer new research opportunities but demand high beam quality even at the electron source. Electron beams generated in an SRF photoinjector hold the potential to fulfill all these requirements. Extracted from photoemission cathodes, the electrons are accelerated in a superconducting cavity to energies of up to several MeV with high gun gradients of several tens MV/m in cw mode.

The aim of an SRF gun is to provide high beam quality at the entrance of the booster as part of the ERL injection line and at the user sample for UED experiments, respectively. The peak brightness B_{peak} represents a figure of merit for the beam quality and thus for the performance of the beam source. It is given by

$$B_{peak} \propto \frac{q_b}{\varepsilon_x \varepsilon_y \sigma_z} \tag{1}$$

with the bunch charge q_b, the transverse emittances ε_x, ε_y and the bunch length σ_z.

The goal is always to maximize the brightness B_{peak}. Therefore, the transverse emittance as well as the bunch length has to be minimized simultaneously, considering the required bunch charges for different applications. This minimization poses a challenge since there is a tradeoff between these two parameters due to the conservation of the 6D emittance, $\varepsilon_{6\mathrm{D}} = const.$ (Liouville's theorem):

$$\varepsilon_{6\mathrm{D}} \propto \varepsilon_r^2 \sigma_z \quad \rightarrow \quad \varepsilon_{x,y} \propto \sqrt{1/\sigma_z}$$

Further, the transverse emittance and the bunch length of the space charge dominated beam are greatly affected by drive laser, gun and solenoid parameters. A global optimization of the SRF injector setting is required to achieve a high brightness mode. Multi-objective optimization provides a solution in order to minimize both conflicting objectives while concerning all limiting variables and constraints given by the photoinjector design.

OPTIMIZATION PROGRAM

The aim of the program presented here is to find a solution for a multi-objective problem. The transverse emittance and the longitudinal bunch length represent the objectives of the optimization which have to be minimized. They depend on several decision variables corresponding to the laser, gun and solenoid parameters that impact one or both objectives. As a starting point the optimization program was developed for the design of GunLab – a compact photoinjector test facility at HZB – with fixed geometries of the gun cavity, the solenoid as well as the drive laser [1, 2]. Therefore, the number of free parameters that serve as decision variables in the optimization process is limited to seven in total: Laser spot size, laser pulse length, cathode position relative to the back plane of the gun cavity, electron extraction phase, RF peak field, solenoid position and solenoid field. The ranges of the decision variables, given by the fixed designs, represent limiting factors for the optimization process. Further constraints are the required bunch charge depending on the application of the electron beam and the optimization point in the beamline, where the objectives should be minimized.

The optimization process is implemented in a MATLAB script using the SPEA2 algorithm [3]. The multi-objective generic algorithm (MOGA) uses several iterations (evolutionary) and is elite-preserving over all generations. The starting point of the optimization is an initial population consisting of a defined number of solutions. Each solution corresponds to one complete parameter set generated by randomly assigning values to the decision variables considering their limits. The objectives are evaluated for each solution using ASTRA, a well-established space charge particle tracking program [4]. A dominance criterion is used for the comparison of all solutions that is defined as follows: A feasible solution x_a dominates a feasible solution x_b if x_a is not worse than x_b in all objectives and strictly better in at least one objective, where "better" means smaller emittance and/or bunch length [5]. Selecting the most dominant solutions in each iteration moves the randomly selected solutions of the initial population to the Pareto- optimum. Finally, a variator generates offspring solutions in each generation.

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The optimization process stops if the population consists of only dominant solutions which are oscillating around the Pareto-optimum front.

One great challenge in the optimization is to reduce the run time of an iteration including particle tracking with space charge calculations. Since there is no “communication” between different solutions up to the point in the process, where the parameter settings are compared in relation to their domination, parallel processing can be used, which is realized on a 64 processor cluster.

RESULTS FOR AN ERL APPLICATION

The commissioning of the energy recovery linac test facility bERLinPro is planned for the next years at Helmholtz-Zentrum Berlin [6]. The target parameters are flexible for development and research mode but geared to operation as a light source. Table 1 summarizes the most important beam parameters of the bERLinPro project. Furthermore, the HZB runs GunLab with a diagnostic beamline that serves for research and development purposes for the future electron source of the ERL. The focus for the SRF gun is on a small transverse emittance combined with a short bunch length. The aim of the multi-objective optimization for GunLab is to demonstrate the ability of the SRF gun to generate a high brightness beam for ERL application as well as to determine suitable parameter sets for laser, gun and solenoid for a stable operation.

Table 1: bERLinPro Main Project Parameters

Total beam energy	50 MeV
Maximum average current	100 mA
Bunch charge	77 pC
Bunch repetition rate	1.3 GHz
Emittance (normalized)	$\leq 1.0\ \pi$ mm mrad
Bunch length (rms)	≤ 2.0 ps (≤ 6.0 ps gun)

Figure 1 shows the first optimization results at the emittance evaluation point in the diagnostic beamline (slit mask) 2.5 m behind the photocathode for two different bunch charges. 7 pC corresponds to a low current commissioning and diagnostic mode. bERLinPro aims for 77 pC bunch charge for 100 mA high average current. Compared to the low current mode, the higher space charge at 77 pC leads to an emittance growth in the transverse plane at same bunch lengths.

The table in Fig. 1 presents the decision variables of one 77 pC beam setting (highlighted). The achieved emittance [$\varepsilon_x = 0.78$ mm mrad] at the emittance compensation point is given by a slice alignment of the bunch by the solenoid. This point is next to the transverse focal point of the beam which enables also a small spot [$\sigma_x = 0.46$ mm @ $z = 2.5$ m]. The focusing in the longitudinal plane and therefore the bunch length minimum depends on the cavity field and the applied energy chirp from the chosen injection phase (velocity bunching) [$\sigma_z = 0.53$ mm].

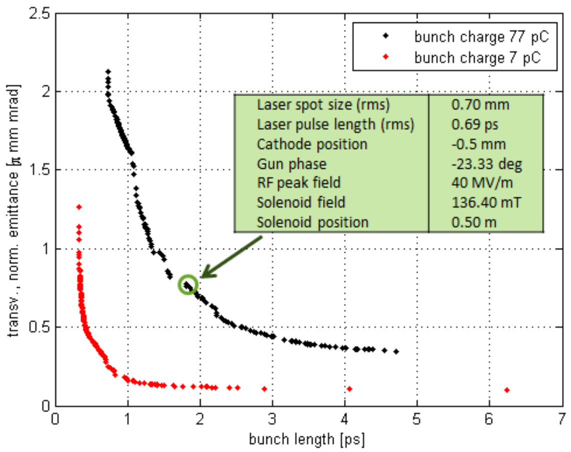

Figure 1: Pareto curves for 7 pC and 77 pC.

Figure 2 plots the curves of the 77 pC multi-objective optimization for different gun gradients. The result confirms the demand for high RF fields in the gun cavity. The values of both objectives can be significantly decreased with higher gun gradients and thus at higher beam energies. Gun parameter settings that fulfill the requirements of bERLinPro ($\varepsilon_x < 1$ mm mrad and $\sigma_z < 6\ ps$) can be found for 77pC bunch charge at gun gradients above 20 MV/m.

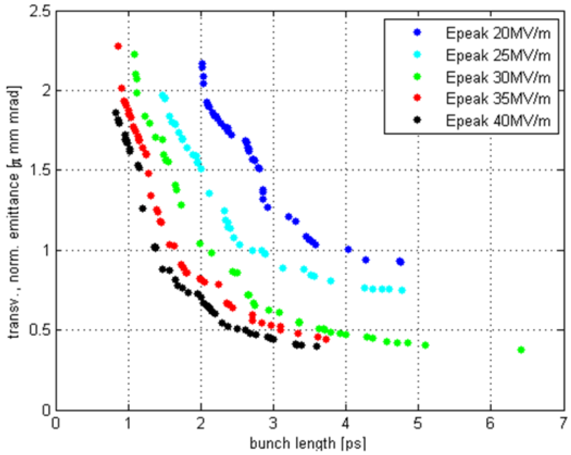

Figure 2: Pareto curves for different gun gradients [20 MV/m … 40 MV/m] with 77 pC bunch charge.

All other decision variables also impact the objectives. The Pareto-optimum front at small bunch lengths is determined by “pancake”-like bunch distributions, given by short laser pulse lengths $\sigma_{\mathrm{laser},z} = 0.9 \dots 3.1$ ps and big laser spot sizes $\sigma_{\mathrm{laser},x} = 1.3 \dots 1.5$ mm [Fig. 3]. The final bunch length is further decreased by velocity bunching with gun injection phases on the negative slope relative to the on crest phase. Smaller emittances are achieved in a “cigar”-regime. Longer pulses $\sigma_{\mathrm{laser},z} = 5.3 \dots 8.6$ ps allow smaller laser spots $\sigma_{\mathrm{laser},x} = 0.3 \dots 0.7$ mm that minimize the intrinsic emittance. Gun phases close to the on crest phase lead to moderate longitudinal focusing but maximum acceleration. In addition, a cathode retreat up to 1.5 mm is used in the “cigar”-regime to decrease emittance by RF focusing.

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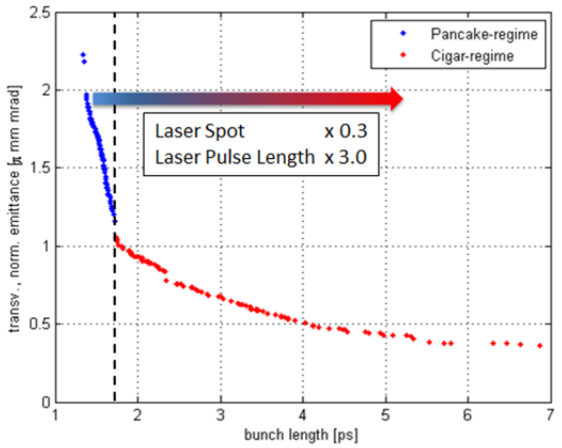

Figure 3: “Pancake”- and “cigar”- like bunch distributions in the Pareto front.

RESULTS FOR A UED APPLICATION

The application of an SRF photoinjector as a user facility is a future perspective at HZB. There is a growing interest in material science, biology or chemistry to analyze not only the static structure but also the structural dynamics of different materials on an atomic level. Electrons offer a good alternative to x-ray photons as they provide larger scattering cross sections in matter for comparable wavelengths. There are challenging requirements on the beam that should hit the sample, including the electron bunches being relativistic, ultra-short (fs regime), compact (µm spot size) with high repetition rates (up to MHz). Nevertheless, these can be fulfilled with the electron beam of an SRF gun.

Ultrafast electron diffraction is typically carried out as a pump-probe experiment [7]. The electron probe beam strikes the sample after being excited by a fs laser pulse (pump beam). The diffraction patterns, detected by a high sensitivity camera, give information about the structure of the sample as a function of pump-probe delay time. The beam quality at the sample defines the temporal and spatial resolution and therefore the quality of the diffraction pattern. As for the ERL, the required high brightness is achieved by minimizing the transverse emittance and bunch length while controlling the beam size at the sample. The same cavity and solenoid designs were used in the optimization code as before. The ps regime drive laser for ERL application was replaced by a laser with fs long pulses. The bunch charge was reduced to a few fC. The optimization stops at the sample chamber, here at 2.5 m behind the photocathode. Figure 4 shows the Pareto-optimum curve for 10 fC bunch charge. As a result, some parameter sets on the Pareto front satisfy the desired bunch length smaller than 20 fs, allowing for a correspondingly high temporal resolution in combination with suitably short and well-synchronized laser pulses. Thus, even ultrafast processes in the sample can be visualized. In spite of the short pulse length there is no significant growth in the transverse plane. Additional apertures can be added to the beamline if a transverse spot size < 200 µm is required at the sample.

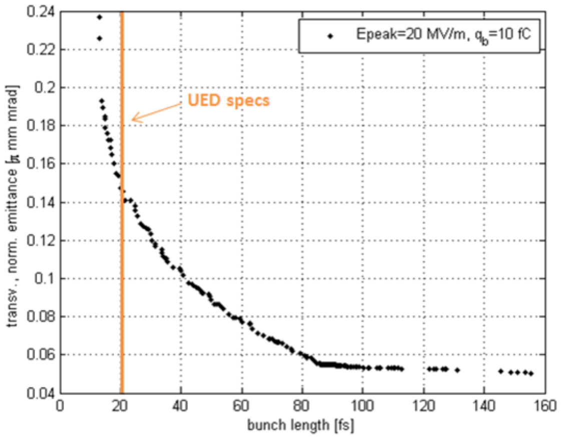

Figure 4: Pareto-optimum curve for 10 fC.

CONCLUSION AND OUTLOOK

The optimization program presented provides a powerful tool to find a stable parameter set for any SRF gun in order to generate a high brightness electron beam. Additionally, the dependence of the objectives on decision variables as well as the impact of space charge effects is analyzed during the optimization. The beam brightness limit of an SRF gun can be found.

The optimization program can be varied or extended by adding further decision variables like the temporal or spatial laser profile, cavity design parameters or booster cavities. Since a universal optimization criterion is applied, any parameters obtained from the ASTRA simulations can be optimized as objectives. First optimizations of transverse coherence length over bunch length were performed for a UED project.

The next step will be to verify the optimization results for an ERL with measurements in GunLab and then to adjust the optimization model. Therefore, the focus will be on the impact of different cathode materials and dark current. Anyway, a good approximation of the optimization is expected since the simulation code makes use of real RF fields and it considers space charge.

Apertures and an additional focusing solenoid will complete the simulated beamline in the UED project. A first pilot experiment for static electron diffraction is planned in cooperation with the Max-Born-Institut in GunLab using parameter settings obtained from first optimizations.

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