ASTRA BASED SWARM OPTIMIZATIONS OF THE B*ERL*inPro INJECTOR

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Abstract

The Berlin Energy Recovery Linac Project B*ERL*inPro is a compact ERL to develop the accelerator physics and technology required to generate and accelerate a 100-mA, 1-mm mrad normalized emittance beam. One of the project challenges is to generate a beam of this kind in the injector line of the machine. Extensive injector optimization studies have been done over the last years. A deep insight in the physics of high brilliance, low energy beams together with single parameter scans allowed for an efficient optimization, resulting in a layout, capable to deliver bunches of the needed charge and dimension. However, changes in the injector components' technical layout, as they are unavoidable in the current stage of the project, may require re-optimizations at any time, if necessary of the whole injector part. To support these work an ASTRA based 'swarm optimization' tool for massive parallel calculations on the institute's Linux computing cluster has been developed. Once the optimization wrapper code is written, results come for free and can help to extend the understanding of the underlying physics. Strategy, procedure and results of the 'swarm optimizations' will be presented in this paper.

INTRODUCTION

B*ERL*inPro [1] is a Energy Recovery Linac (ERL) Project of the "Helmholtz-Zentrum Berlin für Materialien und Energie", funded in 2011. ERLs combine the advantages of linear accelerators (linac) and storage rings: since in principle like linacs, the excellent beam properties of photo-injector electron sources, as they became available in the last years, can be used in an ERL in contrast to storage rings, where the beam parameters arise from an equilibrium state of excitation and damping processes. In addition adiabatic damping while acceleration as well as beam manipulation techniques (e.g. bunch compression) further improve the ERL's beam quality.

In contrast to storage rings, the complete beam energy is dumped in a linear accelerator, limiting the maximum average currents to small values. In ERLs the invested energy is recovered by re-passing the initially accelerating RF structures a second time on a decelerating phase, so that the beam energy restores the cavity fields. Average currents of cw operated ERLs, using super conducting RF technology, become thus comparable to those of storage rings.

B*ERL*inPro's primary function is to demonstrate a stable and reliable low emittance, high-current operation, proving the ERL to be suited for the variety of future applications, including 4^{th} generation X-ray and Compton sources, EUV lithography and nuclear physics. The main B*ERL*inPro parameter are listed in Table 1.

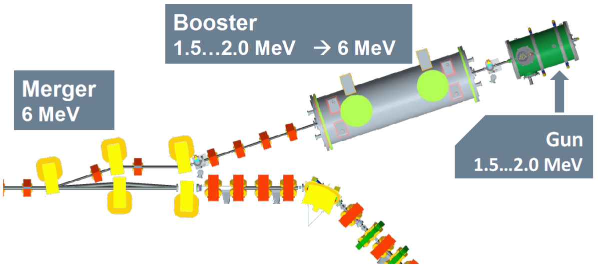

Figure 1: Layout of the B*ERL*inPro Injector, including the modules of the photo cathode gun and the booster linac as well as a dipole dogleg, merging the injector beam onto the main linac / recirculator beam path.

Table 1: Main B*ERL*inPro Parameters in "Standard Mode" Operation

Parameter	Value	Unit
Beam energy	50	MeV
Beam current @ 1.3 GHz	100	mA
Bunch charge	77	pC
Bunch length	~ 2	ps
Energy spread	0.5%	-
Emittance (norm.)	$\simeq 1$	mm mrad
Beam loss	$< 10^{-5}$	-

As the ERL bunch parameters a determined by those of the electron source the injector is one of an ERL's key aspects. To reach normalized emittances of about 1 π mm mrad and below not only a high performance gun is required but also a sophisticated injector setup for emittance conserving acceleration and transport of a strongly space charge (SC) dominated electron beam.

Injector beam line design aims for a trade-off in the bunch dimensions, minimizing the beam distortions due to SC effects, aberrations and RF-nonlinearities. In addition an effective emittance compensation scheme is mandatory.

Figure 1 shows a sketch of the B*ERL*inPro injector, as presented in the Conceptual Design Report (CDR) [2]. Main components are

- a 0.6 cell gun cavity, followed by a sc solenoid also integrated in the gun module, the photo cathode laser has a uniform transverse and a Gaussian longitudinal profile,
- a three 2-cell booster cavities (cavity and module are based on a Cornell design), due to limited RF power at high currents one of the cavities will be operated only at "zero crossing",
- a three bend, 18° dogleg, with quadrupole magnets, both in front of the merger to control the transverse beam size and inside the merger to control the dispersion.

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A setup, satisfying the project requirements of $\varepsilon_{n,xy} < 1.0$ mm mrad, has been found as result of extensive injector studies. These are mostly done using ASTRA [3], a "Particle in Cell" code including SC effects. Numerous single parameter scans and experience based "trial and error" parameter settings are usually required to optimize the injector beam line. In the current project phase changes of parameter limits (e.g. max. field gradients), geometry or even of hardware (e.g. gun cavity design) are unavoidable. To support the time consuming injector setup work an ASTRA based automatic optimizer has been developed as an additional tool. The program is written to run on the HZB high-performance-computing cluster with 31 knots / 820 CPU-cores and a 64-bit OpenSuse Linux OS. The optimizer acts as a wrapper for ASTRA, which is used in its serial version but with many instances running at the same time.

THE OPTIMIZER PROGRAM

The program is written in Fortran and compiled with a freely available Intel compiler. Before running the program a set of reference ASTRA files must be created, where all parameters to be varied are replaced by variable names. The general beam line design is included in these files.

In the beginning of the program the parameters to be varied are read together with their start values and initial variation ranges. The parameters of the initial particle distribution as well as position and field strength of cavities (RF-fields), solenoids and quadrupoles can be varied. For RF fields of course also the phase variations are possible. Due to the implications for the geometry of the downstream beam line dipole magnets may not be varied at the moment. With randomly varied parameters the program generates for each run all required ASTRA files including the particle input distribution. It starts the according batch job, running the distribution generator and one ore more ASTRA runs. When the job has finished the optimizer collects the results, namely the target beam parameters like transverse and longitudinal bunch sizes, divergences and emittances but also energy and energy spread. From these values a weighted goal function is calculated. This function value is to be minimized by the program in an iterative approach: based on the best result found in the previous runs, parameters with small variations are generated for the next iteration. Convergence is reached by lowering the variation range every time no improvement has been found during a defined number of last runs. Since the program runs many ASTRA jobs in parallel a kind of "swarm" search is performed and accordingly we name this kind of optimization.

Special care had to be taken to correctly handle:

- variations in position: overlap of hardware has to be avoided. This is done by defining some reserved space up- and downstream of each elements.
- fixed distances of elements: e.g. for modules containing RF cavities the module position might be varied, while the distance between cavities is fixed. For those cases a flag can be set, freezing the distance to the previous element.
- ASTRA long runs: starting with large variation from a stable solution or even from an unstable one extremely long ASTRA runs may occur. Therefore the run time of each job is controlled and jobs, exceeding a defined maximum run time, will be canceled.
- jobs with two or more successive ASTRA runs: splitting a beam line is convenient, whenever a permanent change in the particles direction of motion occurs. With a pure motion in z, the geometry description in the input file significantly simplifies. To do so the output phase space must be rotated and correct job assignment of input files has to be guaranteed.

SWARM OPTIMIZATION OF THE B*ERL*inPro INJECTOR

Although very recently completed a variety of general program tests, mostly concerning the setup and interaction of ASTRA runs, its result analysis and the job control on the cluster have already been completed. Moreover first optimizations of a full beam line have been started for the B*ERL*inPro injector. Aim of these studies is to verify and - if possible - to improve the injector performance of the setup described in detail in the CDR.

Figure 2 shows the B*ERL*inPro injector elements, relevant for beam dynamics simulations and optimization. The following parameters were used within the swarm optimization: the laser spot size and pulse length on the cathode, the gun cavity's field and phase, the solenoid field strength, the booster cavity fields and phases (phase fixed to "zero crossing" for the first cavity) and the quadrupole magnets upstream, inside and downstream the merger. No parameters of the main linac cavities are varied, but since the SC driven plasma oscillation freezes only at sufficiently high energies the simulations need to be performed until the linac's end. Neither positions nor dimensions of elements have been used for optimization.

The goal function is basically calculated from the transverse projected emittances at the main linac end. An energy

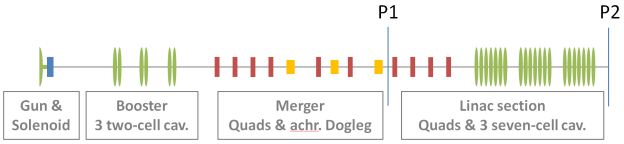
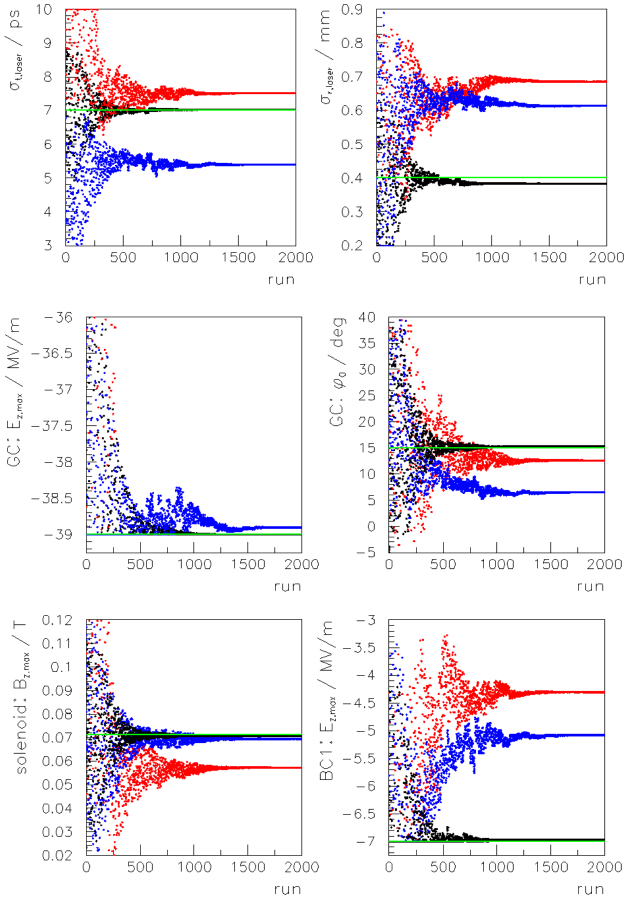


Figure 2: B*ERL*inPro Injector elements used for the optimization: gun, booster and main linac cavities (light green), the gun solenoid (dark green), the three merger bends (yellow) and ten quadrupoles (red). The beam line and thus the ASTRA run is split at P1, right after the last merger bend, where the beam has changed its direction.



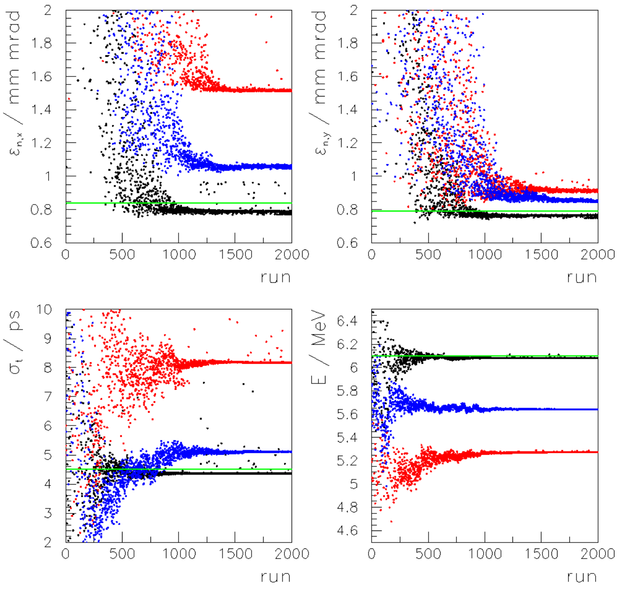


Figure 3: Swarm optimization results starting from the "CDR case" (black) and two modified parameter sets (blue and red). On the left side variations of some exemplary parameters, used within the optimization, are shown: laser pulse duration and spot size (top row), gun cavity gradient and phase (middle row) and the solenoid field and the field of the first booster cavity (bottom row). Figures above show the evolution of the x- and y-emittance during the program run (top row) as well as the bunch length and energy from booster (bottom row). The reference values from the "CDR case" are represented by the green line in each plot.

$\geq$ 6 MeV from the booster as well as a final bunch length $\leq$ 4.5 ps are also implemented in the goal function. A typical single ASTRA run with 2000 particles takes about 15 minutes. Using the 64 cores (max. number per user) the optimization is an "over-night" run of about 6-12 hours.

Starting with the "CDR case" the optimizer found a solution with both emittances reduced by a few percent, still satisfying the energy and bunch length requirements. Starting with modified parameters the optimizer does not reach the performance of the CDR case, neither in emittance nor in energy and bunch length. Results of selected optimizations are presented in Fig. 3. They indicate that the quality of the optimization result sensitively depends on the optimization time, the definition of the goal function but especially on the start setup together with the applied variation ranges. More tests of the program are needed to clarify the requirements of a successful optimization. To increase the number of jobs per time unit ASTRA run tests with less particles will be executed, maybe also more than 64 cores might become available. If this is successful the convergence causing reduction of each parameters variation range needs to be investigated in more detail. Maybe more sophisticated procedures like e.g. "simulated annealing" will be required.

CONCLUSION & OUTLOOK

Although not generally able to find the CDR solution, the optimizer proved its capability to improve from a given start setting. Even starting with the extensively optimized "CDR case" a setup with a slightly lower emittance could still be found. More advanced analysis tools of the results will be necessary to uncover correlations between parameters and performance or to evaluate distribution features like shape distortions or beam halo.

A next application will be a comparison of an 0.4 / 1.4 cell gun cavity based injector for B*ERL*inPro .

REFERENCES

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[2] "Conceptual Design Report B*ERL*inPro ", editors: A. Jankowiak, J.Knobloch, B. Kuske, N. Paulick, 2012.

[3] K. Flöttmann, ASTRA - A Space Charge Tracking Algorithm, Version 3.0, `http://www.desy.de/~mpyflo/astra`.