LOW EMITTANCE ELECTRON BEAMS FOR THE RHIC ELECTRON COOLER

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Abstract

An electron cooler, based on an Energy Recovery Linac (ERL) is under development for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. This will be the first electron cooler operating at high energy with bunched beams. In order to achieve sufficient cooling of the ion beams the electron have to have a charge of 5 nC and a normalized emittance less than 4 μ. This paper presents the progress in optimizing the injector and the emittance improvements from shaping the charge distribution in the bunch.

INTRODUCTION

The RHIC electron cooler requires an electron beam with a bunch charge of 5 nC, a normalized emittance of less than 4 μ and an energy spread of less than $6 \cdot 10^{-4}$. The beam is created in a 1½ cell SRF electron gun, where it is accelerated to about 5 MeV. It is then focused by a solenoid and passes the dipole merging system, where the used bunches are injected back into the accelerating cavities for energy recovery. Because of the low beam energy in this region the beam dynamics is strongly influenced by the space charge forces and some emittance increase is unavoidable. Through careful optimization of the beam size, focusing and timing the beam emittance is minimized at the exit of the linac.

There are two new technologies under development that may improve the beam quality of the cooler injector: The first is the diamond cathode, which uses a thin diamond window to amplify a primary electron beam by two orders of magnitude. Besides a simplification of the laser and vacuum system this cathode may reduce the transverse temperature of the electrons from the typical 0.3 eV to about 0.1 eV.

The second development tries to shape the electron bunch by shaping the spatial dimensions of the laser pulse. The creation of a cylindrical distribution (beer can) is established technology. A better, but more difficult shape is an ellipsoid, where space charge fields inside the bunch are linear. The shape can be improved when the ellipsoid is slightly deformed (tear drop) to counteract space charge effects during the emission from the cathode.

OPTIMIZATION PROCESS

The CONDOR optimizer [1] is used for the optimization. This package was developed for the aircraft industry and is aimed at "expensive and noisy" calculations, such as chemical reactions and turbine design and is an algorithmic extension of Powell's UOBYQA algorithm ("*Unconstrained Optimization by Quadratical Approximation*"). The algorithm brackets the minimum in n-dimensional space and does not use derivatives calculated from differences. The initial step size is therefore chosen as large as possible which reduces the influence of noise. In our case the noise is caused by the limited number of tracked particles and the number of bins in the space charge calculation.

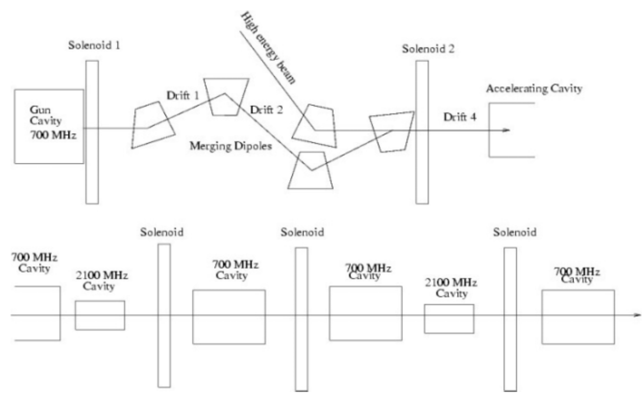

Figure 1:Layout of the injector and linac. The system has two solenoids for emittance compensation, a Z-bend merging system, for 700 MHz accelerationg cavities and two 2100 MHz decelerating cavities to minimize the energy spread of the beam.

The emittance blow-up is caused by three mechanisms:

- The non-linearity of the transverse space charge forces and external fields. There is some cancellation if the beam size is chosen correctly.
- The longitudinal variation of the linear forces caused by the time dependence of the fields and the charge distribution in the bunch. This can be mitigated by the process of emittance compensation [2]: by carefully choosing the focusing and drift length after the gun the space charge itself can be used to reverse the emittance blow up.
- The dispersion of the merging system. This causes coupling of the longitudinal motion into the transverse direction. By using the Z-bend system [3] this effect is strongly reduced.
- Chromaticity: This can be minimized using two solenoids in the emittance compensation [4].

The following parameters are used to minimize the emittance blow-up:

- The beam radius and length. Enlarging the radius will reduce the space charge forces, but increase the

* Work performed under the auspices of the U.S .Department of Energy

1-4244-0917-9/07/$25.00

thermal emittance. Enlarging the bunch length reduces the space charge forces, but increases the energy spread and the effect of chromaticity.

- The gun voltage and start phase. This will influence the time (RF phase) when the bunch passes the center iris of the gun. This affects the transverse focusing by transverse electric fields. It also changes the energy spread of the bunch at the exit of the gun, which causes emittance growth through chromaticity. The energy spread is therefore another quality indicator (with a lesser weight).
- The focusing with two solenoids and distance between the gun and the linac are used for emittance compensation.
- The drift length between the merging dipoles minimizes the longitudinal-transverse coupling.

It is important to find a good starting point for the optimization, so that the optimizer does not get stuck in a local minimum. The optimization also becomes more complex and time consuming with the number of variables. Therefore the optimization is performed in multiple steps:

1. The first step finds a good starting point for the gun parameters. The sum of the slice emittances is minimized at the exit of the gun. The program PARMELA [5] is used for the function evaluation. 250000 particles are tracked and the slice emittances are calculated for 500 longitudinal slices. Those emittances are the added quadratically, weighted by the number of particles in the slice. This gives a measure of the beam quality that excludes the first blow-up mechanism. The result would be the best parameter set if the following emittance compensation is perfect. The bunch length was fixed to ±10 degrees. Including the bunch length as a parameter resulted either in a minimal change or in a worse result.
2. The second step finds a starting point for the optics from the exit of the gun to the exit of the first linac cavity using the program SLENV [6]. SLENV integrates the slice envelopes of the bunch using the well-known differential equation and calculate an approximate emittance. The function evaluation takes less than 1 second (compared to 45 minutes for PARMELA) and allows rapid scanning of the parameter space. Parameters are the solenoid strength and the drift length between the solenoid and the accelerating cavity. SLENV is also used to minimize the dispersion in the merging section.
3. The beam line is set up according to the SLENV results. The cavity phases are optimized to minimize the energy spread throughout the linac. This is done with 20000 particles to save time
4. The same optimization as in step 2 is then performed using PARMELA for the function evaluation, using the SLENV results as a start point. The drift lengths between the Z-bend dipoles are used as additional optimization parameters. The figures of merit are the projected emittances at two locations downstream of the first accelerating cavity with a solenoid between these points. If only one location is used the optimizer will try to make the beam size in the observation point zero, resulting in an optimal emittance in this point and a strong emittance growth afterwards.
5. Next the whole system is optimized with PARMELA. All parameters except the Z-bend drifts are used. An improvement of 10%-25% is achieved in this step.
6. Finally the cavity phases and the amplitude of the 3rd harmonic cavity in the linac are adjusted to minimize the energy spread at the end of the linac.

RESULTS

The results of the optimization are summarized in Table 1. Two values for the emittance are given for each case: the minimum emittance inside the linac and the emittance at the end of the linac. In some cases there is a significant increase in the linac. We assume that varying the solenoid focusing in the linac can further optimize these cases. This is ongoing work.

This optimization shows that the requirements for the cooler are met with conventional technology using a beer can distribution and a cathode with 0.3 eV transverse temperature. With an emittance of 2.95 μ for the ideal machine the is a reasonable budget for the real world (misalignments, etc.)

Not much is gained when the cathode temperature is lowered with the beer can distribution because the space charge force makes the dominant contribution to the emittance.

A much better improvement is gained from using the tear drop shape. The emittance is reduced by 30% or, when coupled with a lower cathode temperature, by 66%. Alternatively, one can increase the bunch charge to 10 nC and reduce the cooling time by a factor of two.

REFERENCES

[1] Frank Vanden Berghen: Optimization algorithm for Non-Linear, Constrained, Derivative-free optimization of Continuous, High-computing-load, Noisy Objective Functions. http://iridia.ulb.ac.be/_fvandenb/work/thesis/.

[2] L. Serafini, J. B. Rosenzweig, Phys. Rev E55, 7565, (1997)

[3] Novel Method of Emittance Preservation in ERL Merging System in Presence of Strong Space Charge Forces, D. Kayran, V.N. Litvinenko, WPAP037, these proceedings

[4] X.Y. Chang, I. Ben-Zvi, J. Kewisch, Phys. Rev ST AB 9, 044201, (2006)

[5] L. M. Young: Parmela, LANL, LA-UR-96-1835

[6] Jörg Kewisch, Xiangyun Chang: Emittance Compensation for Magnetized Beams, this conference THPMS088

Table 1: Optimization Results

Bunch shape	Transverse Temperature	Bunch charge [nC]	Parmela optimized Emittance in the middle of the linac	Parmela optimized Emittance at the exit of the linac	Energy spread
Beer Can	0.1 eV	5 nC	2.300	2.992	1.20e-3
		7 nC	2.779	3.626	5.22e-4
		10 nC	5.220	5.364	1.58e-3
	0.3 eV	5 nC	2.908	2.941	2.11e-4
		7 nC	3.508	4.047	2.64e-4
		10 nC	7.031	7.773	5.39e-4
Tear Drop	0.1 eV	5 nC	0.915	0.917	2.84e-4
		7 nC	1.247	1.448	2.80e-4
		10 nC	2.235	3.282	3.44e-4
	0.3 eV	5 nC	2.066	2.166	3.00e-4
		7 nC	2.464	2.711	8.16e-4
		10 nC	2.586	2.643	3.44e-4

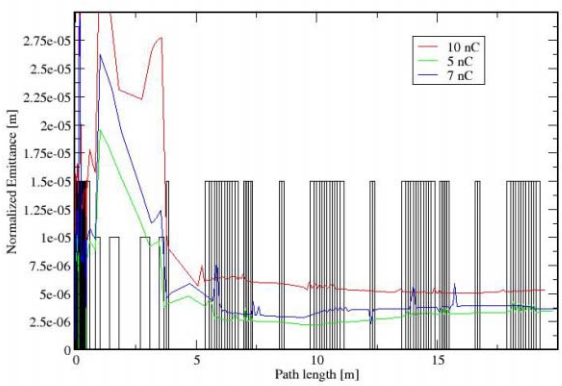

Figure 2: Emittances for beer can distributions with 0.1 eV cathode temperature.

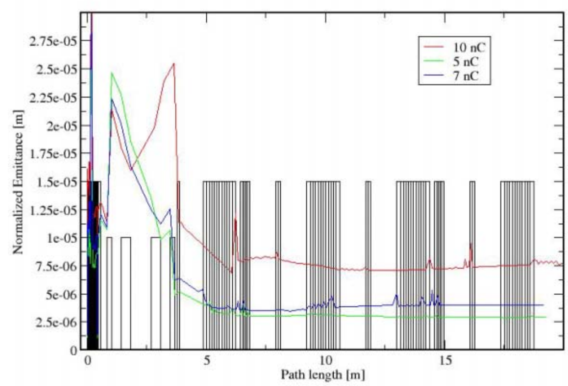

Figure 4: Emittances tear drop distributions with 0.1 eV cathode temperature.

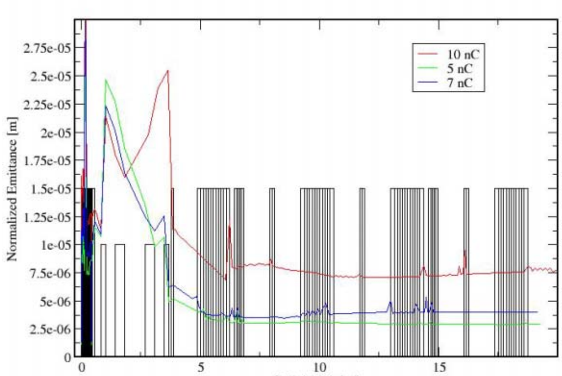

Figure 3: Emittances for beer can distributions with 0.3 eV cathode temperature.

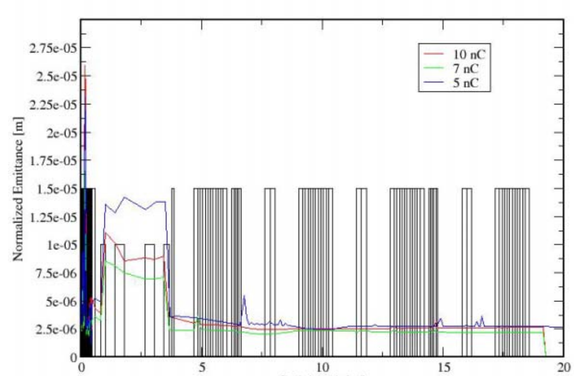

Figure 5: Emittances for tear drop distributions with 0.3 eV cathode temperature.

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