EMITTANCE COMPENSATION IN FLAT BEAM PRODUCTION IN AN RF GUN LINAC*

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Abstract

Fermilab/NICADD Photoinjector Laboratory has performed a lot of experiments on flat beam production with Ya. Derbenev proposed skew quadrupole channel method [1]. A ratio of 50 of the transverse emittances in X and Y planes has been achieved. In both experiments and simulations with PARMELA [2], the resulted flat beam shows an S-shaped distribution in X-Y space. The sources of the S distribution has been investigated in this paper. A compensation method was suggested to straighten the S distribution and improve the emittance ratio. With this method, an extra solenoid located before the superconducting cavity is added to adjust the beam transverse size when the beam passes through the cavity. PARMELA simulations have shown that, with proper setup of this extra solenoid, the emittance ratio can be enhanced by a factor of about 1.6 and the S-shaped transverse distribution can also be greatly removed.

INTRODUCTION

Flat beam transformation

When a particle travels along the axis of a solenoid field, its transverse movements can be decoupled in the rotating Larmor frame. The radial distance from the particle to the axis and the transverse momentum characterise the two decoupled motions. At the end of the solenoid, the particle gains a side kick, and the two decoupled motions in Larmor frame are transformed into two rotations around the solenoid axis with angular momentum of different signs. The motion constants of these two angular momentum dominated beam can be connected with the status of particle when it is in the solenoid:

$$\varepsilon_+ = \frac{d^2 eB}{p_s}, \quad \varepsilon_- = \frac{p_\perp^2}{eBp_s} \tag{1}$$

where p_s is the longitudinal momentum, B is the solenoid magnetic field, d is distance from particle to the axis, e is particle charge. For an electron born in solenoid field from the photo cathode in RF gun, its transverse momentum $p_\perp$ is very small, which makes $\varepsilon_+ \gg \varepsilon_-$ [3].

Ya. Derbenev suggested to use a skew-quadrupole triplet to remove the angular momentum of the particle and map $(\varepsilon_+, \varepsilon_-)$ to $(\varepsilon_x, \varepsilon_y)$, where, $\varepsilon_{x,y}$ are emittances in X and Y planes after transformation. This transformation can be realized under conditions:

$$\beta_x = \beta_y, \quad \alpha_x = \alpha_y, \quad \Delta\Phi_y = \Delta\Phi_x + \frac{\pi}{2} \tag{2}$$

where $\beta_{x,y}$, $\alpha_{x,y}$ are Twiss parameters at the exit of the skew-quadrupole triplet, and $\Delta\Phi_{x,y}$ are betatron phase advance over the skew-quadrupole triplet region.

Experimental setup

Fermilab/NICADD Photoinjector Laboratory experimental setup [4] is briefly described here, more details can be found in their earlier papers. A 1.3 GHz, one and half cell RF gun with Cs_2Te photo cathode produces an electron bunch of 3.5 MeV energy and 1 nC charge. The electron bunch is transported into the downstream 9-cell TESLA type superconducting cavity and is accelerated to around 16 MeV. A skew-quadrupole triplet sits after the cavity and is used as the flat beam adaptor. There is a solenoid located in RF gun region, which provides focusing and initial angular momentum for the flat beam production. By adjusting the solenoid and skew-quadrupole field, a flat beam can be obtained when above mentioned conditions are matched.

S-SHAPED DISTRIBUTION OBSERVATION

In experiments, a flat beam of more or less S-shaped distribution is often observed, as shown in left portion of Fig. 1, which are as presented at LINAC 2000 [5]. This S-shape can not be removed by adjusting skew-quadrupole field to make a better match to the beam. Obviously, if we can straighten the distribution, then we can obtain a higher emittance ratio.

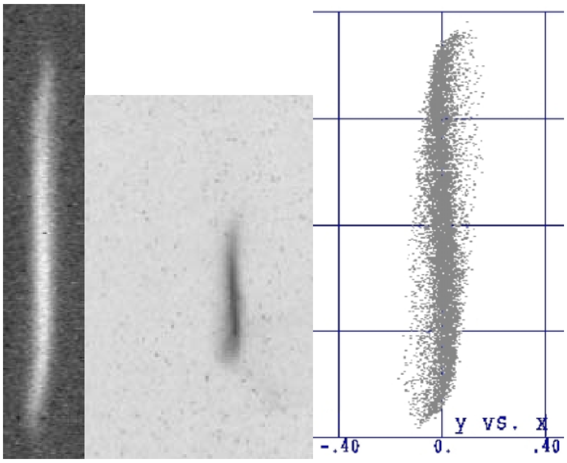

Figure 1: S-shaped distribution observation

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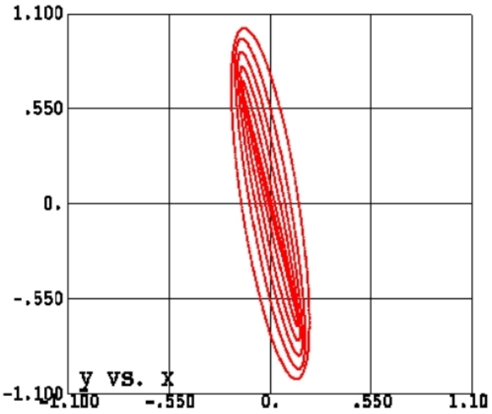

Figure 2: S-shaped distribution with simplified model.

We use PARMELA to simulate the flat beam production process. And we found the S-shaped distribution in simulation, too, as shown in the right portion of Fig. 1. We tried to pin-point the sources of the S-shaped distribution by simplifying the models used in simulations. First, we chopped the bunch in energy domain, the resulted bunch has very small energy spread, but we still can see the S-shaped distribution. Then, an artificial slice is used. Hundreds of macro particles are initialy distributed into ten circles with radius uniformly spaced. Obviously, no space charge effect is considered here. We have those circles born in solenoid field, and directly go through the skew-quadrupole triplet after getting out of the solenoid field. In this way, we can produce a flat beam of extremely high emittance ratio, and no S-shaped distribution is observed. If we let those circles be accelerated by the 9-cell cavity before they enter the skew-quadrupole triplet, the S-shaped distribution can be clearly seen in the final flat beam, as shown in Fig. 2.

After it is clear that the 9-cell cavity is one possible source of the S-shaped distribution, we look into the transverse phase space before and after the cavity. In Fig.3, the upper portion is the phase space distribution before cavity, and bottom portion after cavity. We can see that the circles in phase space rotate with different rate according to their radius, this means the particles on circles of different radius receive transverse forces which are not linearly proportional to the radius. We also notice that the transverse size of the beam in Fermilab/NICADD photoinjector experimental setup reaches its maximum of 1.2 cm at the entrance of the cavity, and the beam is focused through the cavity. We believe that the big transverse size of the beam let the particles see the nonlinear RF fields near the iris region of the cells in cavity.

FLAT BEAM EMITTANCE COMPENSATION

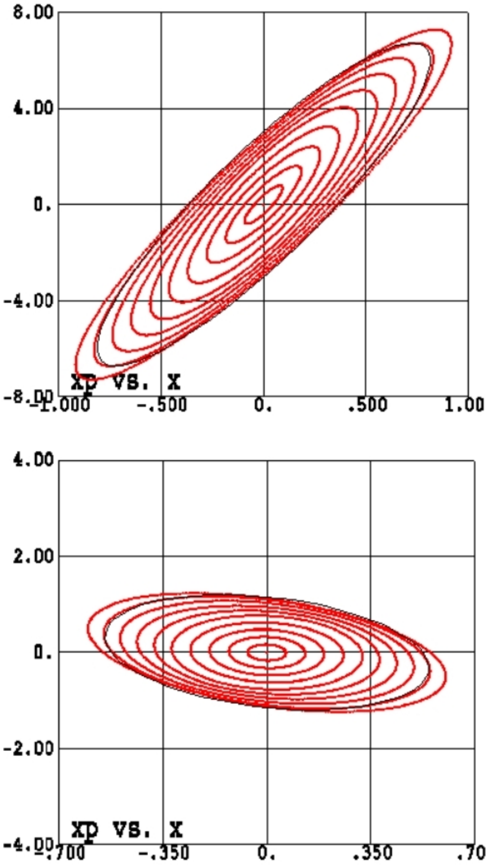

Figure 3: Phase space distribution before and after the cavity.

In reality, things get more complicated with the presence of the space charge forces. But this situation also gives us opportunities to make advantages of it. For a long beam, if the particles are uniformly distributed, the transverse space charge force can be linear. But for non-ideally distributed beam, we usually have nonlinear components in space charge forces. Also one may notice that the transverse force from the cavity RF fields are focusing, and the space charge forces are always defocusing. Hence, it is possible for one to make them to cancel each other.

The implementation of this compensation is to add an additional independent solenoid before the cavity. By tuning this solenoid field, the transverse size of the beam throughout the cavity can be adjusted to some extend. The variation of the transverse size of the beam will change what RF fields particles see and the space charge force simultaneously.

In Fig. 4, the magnetic field both with and without compensation solenoid are shown from cathode to the entrance of the cavity. The respectively resulted X_{rms} profile are shown in Fig. 5. With this compensation solenoid, the parameters of the skew-quadrupole triplet are adjusted to match incoming beam, and the resulted flat beam is shown in the upper portion in Fig.6. Numerical results are shown in Table 1. The emittance ratio of the flat beam increased by a factor of 1.6. Although ε_- gets much smaller then the value without compensation, the space charge effect during the flat beam transformation and the momentum spread

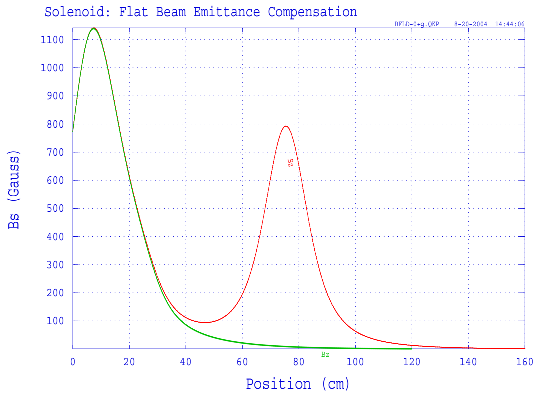

Figure 4: Bs profile situations with(red) and without(green) emittance compensation.

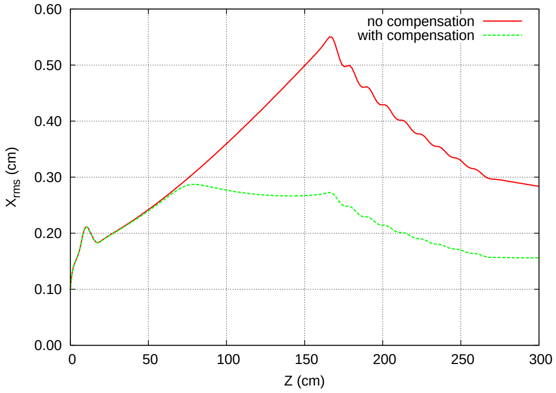

Figure 5: X profile for emittance compensation

limit the efficiency of mapping from ε_- to ε_x.

The result of an over compensated case is also shown in the bottom portion in Fig.6, which exhibit an reversed S-shaped distribution.

Table 1: Transformation results with and without compensation

compensation	$\varepsilon_+(\mu\mathrm{m})$	$\varepsilon_-(\mu\mathrm{m})$	$\varepsilon_x(\mu\mathrm{m})$	$\varepsilon_y(\mu\mathrm{m})$
with	46.28	0.28	0.53	45.87
without	45.04	0.50	0.84	45.95

CONCLUSION

A solenoid is used to make compensation to the nonlinear forces particles see, the compensated emittance of the flat beam is lowered by near 40%. S-shaped distribution is straightened. Momentum spread and space charge effect in skew-quadrupole triplet region might be the next barrier to lower the flat beam emittance even more.

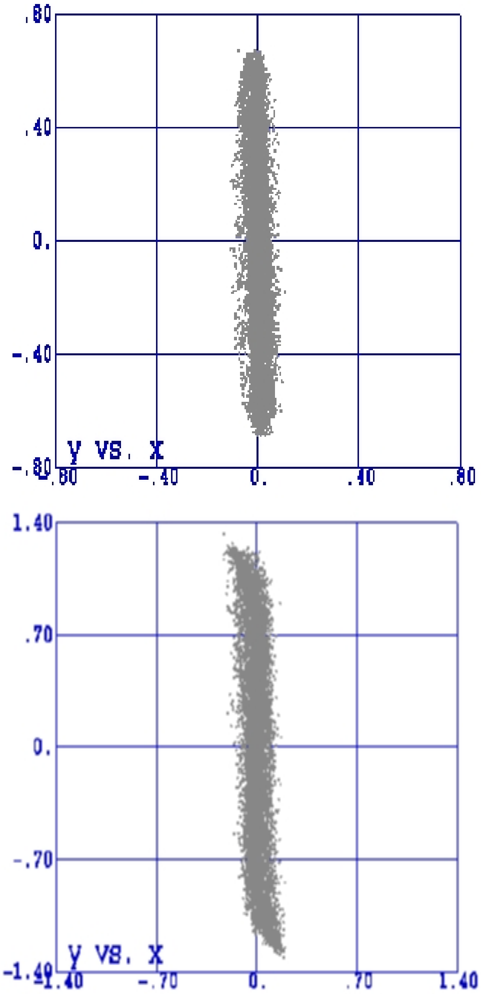

Figure 6: Compensated and over compensated results

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