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## Recommended Modifications on the Current 100 kV Beamline of the Injector Based on Computer Simulations

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### Abstract

This note summarizes simulation results in support of making decisions on modifying the current 100 kV beamline of the injector to ease polarized source operations at full current of 100  $\mu\text{A}$  through a single slit without affecting operation of the thermionic gun. The issues investigated include: (1) adding an additional RF buncher to compress the polarized electron beams prior to the chopping system; and (2) enlarging A1/A2 to increase transmission at high operating currents. Although very challenging due to strong space charge effects, operating this injector at full current of 100  $\mu\text{A}$  with all the nominal specs satisfied can be achieved, if the modifications recommended in this note are implemented.

### 1. Introduction

There have been plans to modify the current 100 kV beamline of the injector to ease its operations at high electron beam current from the polarized source. These plans include: (1) adding an additional RF buncher to compress the polarized electron beams prior to the chopping system; (2) enlarging A1/A2 to increase beam transmission at high operating currents. They have been discussed in regular injector meetings, with some preliminary simulation results evaluated. This note is a full context summary of all the simulations conducted for these plans.

### 2. Comparison of measured bunch length on polarized beams with simulations

Bunch lengthening effects due to space charge on the polarized beams were measured some time ago. Using the PARMELA deck established recently [1] for simulating polarized beam transport, a series of simulations were conducted to compare with the measurements. The purpose of this comparison was to validate the models on which this deck is based. The initial beam conditions used at the cathode are as follows

**Time Structure:** pulsed Gaussian with a *fwhm* of 75 ps;  
**Spatial Structure:** Gaussian with a *fwhm* of 0.5 mm;  
**Energy Distribution:** Gaussian with  $E_{av} = 0.2$  eV,  $\sigma_E = 0.1$  eV;  
**Rep Rate:** 500 MHz;

### Beam Current: variable.

Fig. 1 shows the comparison between measurement and simulation. The measured bunch lengths were given in two different manners, one in *fwhm*, and one in 90% enclosure of beam. As the current became high, the measured bunch length profiles show a significant distortion by space charge, and it is no longer accurate if *fwhm* were used to define the bunch length. For this reason, the 90% beam-enclosure bunch lengths were compared with  $4\sigma$  bunch lengths simulated with the same amount of beam current. It is seen that measurement and simulation agree fairly well with each other.

### 3. Polarized beamline with one additional buncher

As is known, the lifetime of a photoemission gun is one of the most critical issues for meeting the requirement of long-term operations. This requires eliminating any kind of massive beam loss after the gun. Specifically, beam losses through A1/A2 and chopper aperture need be minimized. With this end in mind, several cases were designed and simulated numerically. The results are summarized in Table 1.

In Table 1, Case 0 is the reference case composed of 100  $\mu\text{A}$  thermionic beam, and all the other cases are for the polarized beams. We started with Case 1 that corresponds to 60  $\mu\text{A}$  with an additional buncher positioned at the end of the Z (polarization manipulator). This buncher's phase and amplitude were optimized to be at zero-crossing and 0.0075 MV/m, respectively.  $\Delta\phi_2 = 0$  is given as well to help remind that the second SRF cavity in the unit was phased on-crest. By off-cresting this cavity, one can trade bunch length with energy spread in the 5 MeV region, which is useful to help further bunch the electrons [2]. This parameter was varied in the other cases shown in Table 1.

In the above case, the beam transmission was 83% through A1/A2, and 98% through the chopper aperture (CA). The A1 and A2 diameters were set to 1 mm and 3.5 mm, respectively, as they have been. Two concerns were identified here: (1) beam transmission through A1/A2 is still less than 100%; (2) a bunch length of 2 degrees at Yao 2 is larger than the requirement of 1.4 degrees.

So in Case 2, the second SRF cavity in the unit was off-cresting by 25 degrees, and the bunch length was reduced to 0.69 degrees with the energy spread increased to 43 keV and with the horizontal emittance doubled due to the skew-quad effect from the cavity.

In Case 3, the additional buncher was turned off to see how much beam loss would have occurred without it. It turned out that the transmission through the chopper aperture was dropped by 24%, compared with Cases 1 and 2 with that additional buncher on.

The next case, Case 4, corresponds to an attempt to increase beam transmission through A1/A2, with A1 diameter increased from its current size of 1 mm to 1.5 mm, and with that additional buncher turned on again. The transmission through A1/A2 was increased to 92%.

Case 5 was run to see what would happen if the beam current were increased from 60  $\mu\text{A}$  to 100

$\mu\text{A}$  with nothing else changed. It turned out that the total transmission is  $0.75 \times 0.82 = 62\%$  only, which means if we start with  $100 \mu\text{A}$  from the gun, we would get only  $62 \mu\text{A}$  out of the chopper aperture.

Then in Case 6, we increased A1 diameter to 6 mm which is the aperture size there without A1, and we re-optimized the buncher gradient to  $0.01 \text{ MV/m}$ . These changes allow as much as  $97\%$  transmission of a starting beam current of  $100 \mu\text{A}$  through both A1/A2 and through the chopper aperture. Again, to evaluate the utility of this additional buncher, we turned it off in Case 7 and found that the transmission through the chopper aperture was dropped to  $57\%$ , which is a beam loss level that is unacceptable.

Cases 8 to 11 were to determine phase and amplitude stability requirements on this additional buncher. By imposing a requirement that the transmission through the chopper aperture must be stabilized within  $0.5\%$ , which corresponds to the resolution of actual measurement, it is derived that this buncher's RF phase and amplitude must be stabilized within  $1$  degree and  $1\%$ , respectively.

#### 4. Determination of A1 and A2 diameters

It was realized that the position of that solenoid prior to A1 needs be re-optimized to give highest possible transmission while keeping A1's size as small as possible. Besides, A2's size could be a variable as well. After a few iterations of runs, various options converged to the following point:

**Increase A1 diameter from 1 mm to 2 mm;**  
**Increase A2 diameter from 3.5 mm to 4 mm;**  
**Move lens MFA0I02 toward BU by 10 cm.**

With these changes and an initial beam current of  $110 \mu\text{A}$ , the following simulation results were obtained:

**Transmission through A1/A2 =  $95\%$ ;**  
**Transmission through chopper aperture =  $98\%$ ;**  
**Beam current out of chopper aperture =  $103 \mu\text{A}$ ;**

**Beam parameters @ Yao 2:**

**$4\sigma$  bunch length =  $1.2$  degrees;**  
 **$4\sigma$  energy spread =  $72 \text{ kV}$ ;**  
**Longitudinal emittance =  $1.82 \text{ deg-kV}$ ;**  
 **$\epsilon_{nxrms}/\epsilon_{nyrms} = 0.57/0.24 \text{ mm mr}$ .**

The beam envelopes and phase space distributions @ Yao 2 are shown in Figs. 2 and 3, respectively to help demonstrate the above numerical results.

Since at such a high beam current level, a significant amount of electrons would be driven into a halo surrounding the core of the beam due to space charge effects, further improvement on trans-

mission or 100% beam transmission through A1/A2 would be impossible without making A1 and A2 significantly larger than that can be used to define the initial emittance of the beams. The formation of beam halo has been evidenced by the large ratio of 100% emittance to rms emittance, which is equal to 12 at the gun exit, and equal to 21 prior to A1. See Figs. 4 and 5 for beam distributions at these two locations. Therefore, it is recommended that enlargement of A1 and A2 should go no more than 2 mm in diameter for A1 and 4 mm in diameter for A2.

### **5. Initial emittance defined by A1 and A2**

With A1 = 1 mm (diameter), A2 = 3.5 mm (diameter), and L (separation) = 773.5 mm, the normalized rms emittance defined by these two apertures is 0.11 mm mr. The modified emittance with a larger A1 and a larger A2 would be  $0.11 \times (2 \text{ mm} / 1 \text{ mm}) \times (4 \text{ mm} / 3.5 \text{ mm}) = 0.25 \text{ mm mr}$ , which is a factor of four smaller than the spec of 1 mm mr at 1 GeV. Therefore, the largest initial emittance defined by these two apertures is still much smaller than the spec. With low current electron beams, their intrinsic emittance is smaller than the emittance defined by this emittance filter, so the modifications would not affect low beam current operations.

### **6. Size of the aperture on the master slit**

One remaining question is whether the size of the aperture on the master slit should be changed from 1 mm to 2 mm, if A1's diameter were changed from 1 mm to 2 mm. To answer this question, one run with both chopper cavities turned off was conducted. The beam envelopes from the thermionic gun to the exit of the chopper system are shown in Fig. 6. The beam size at the chopper aperture is 1.5 mm, which is larger than 1 mm but smaller than 2 mm. Based on this, it is recommended that the size of the aperture on the master slit should be increased to 2 mm as well.

### **7. Summary of recommended modifications**

For convenience of implementation considerations, the recommended modifications are summarized as follows:

1. One additional buncher is needed for maximizing polarized beam transmission through the chopper aperture; this buncher should be positioned at the exit of the Z; its phase and amplitude must be stable within 1 degree and 1%, respectively; the operating power required is 25 times lower than that of the nominal buncher downstream, if they were identical;
2. A1's diameter should be increased from 1 mm to 2 mm; and A2's diameter should be increased from 3.5 mm to 4 mm; the emittance defined through A1/A2 will then be about a factor of 4 smaller than the 1 mm mr spec (normalized, rms) at 1 GeV.
3. Lens MFA0I02 should be moved toward BU by 10 cm; the optimal setting of this lens is 914 mA for polarized beams, and is -1114 mA for thermionic beams;
4. The diameter of the aperture on the master slit should be increased to 2 mm as well.

## References

- [1] H. Liu, TJNAF-TN # 96-051.
- [2] D. Wang, private communication.

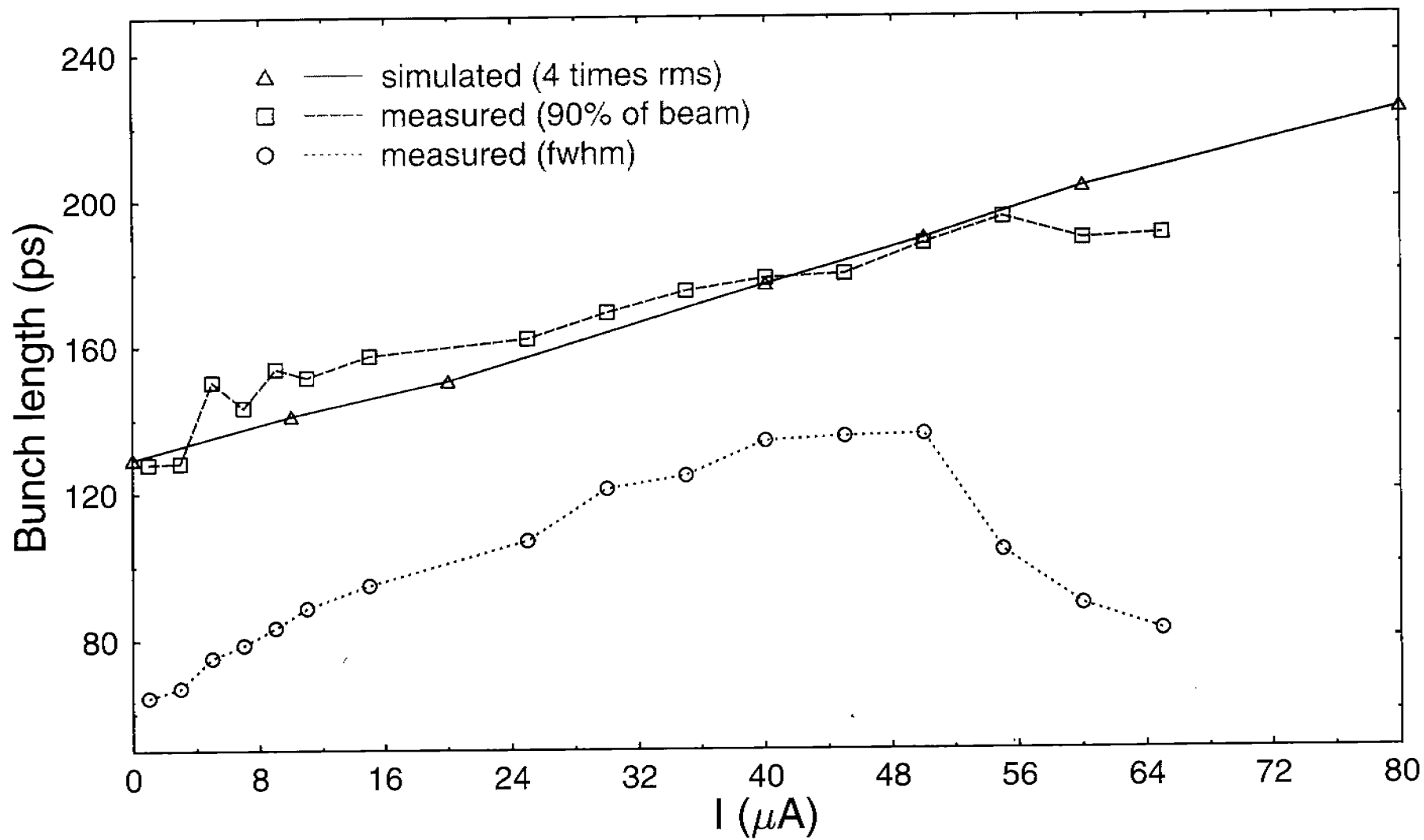


Fig. 1 Analysis of polarized beam bunch length measurement /BLoct.gle: 11:06:07 Thu Dec 5 1996

**Table 1 Simulated results on additional buncher and A1-enlargement/out**

Notes: Bunch length, energy spread and emittance are at Yao 2;  $\Delta\phi_b$  is the off-zero-crossing phase of the additional buncher in deg.,  $E_b$  is the gradient of the additional buncher in MV/m,  $\Delta\phi_2$  is the off-crest phase of the 2nd SRF cavity in the unit. The operating gradient of the nominal buncher downstream is 0.06292 MV/m. The location of this additional buncher is 28.45 cm center-to-center with the last lens of phi-rotator, or 20.75 cm center-to-center with the first lens downstream.

Case #	Case Definition	T1 (%) (Gun - A2)	T2 (%) (A2 - CA)	$4\sigma_\phi$ ( $^\circ$ )	$4\sigma_e$ (kV)	$\epsilon_\phi$ ( $^\circ$ -kV)	$\epsilon_{nx}/\epsilon_{ny}$ (mm mr)
0	reference, thermionic, 100 uA	55	50/3=17	1.5	6	0.612	0.35/0.23
1	60 uA, $\Delta\phi_b = 0$ , $E_b = 0.0075$ MV/m, $\Delta\phi_2 = 0$	83	98	2.0	11	0.639	0.14/0.17
2	60 uA, $\Delta\phi_2 = -25^\circ$ (2nd SRF cav off-crest)	83	98	0.69	43	0.834	0.28/0.14
3	60 uA, $E_b = 0.0$ (additional buncher off)	84	73	0.73	40	1.60	0.29/0.13
4	60 uA, A1 1.5 mm instead of 1 mm, $E_b = 0.0075$	92	98	0.79	41	0.86	0.28/0.15
5	100 uA instead of 60 uA	75	82	0.72	29	0.83	0.21/0.19
6	100 uA, A1 out (6 mm) with $E_b = 0.01$	97	96.7	0.92	51	1.08	0.50/0.25
7	100 uA, $E_b = 0.0$ (additional buncher off)	97	57	1.08	55	2.40	0.42/0.20
8	100 uA, $\Delta\phi_b = -5^\circ$ , $E_b = 0.01$ MV/m	93	98	1.07	53	0.98	0.52/0.24
9	100 uA, $\Delta\phi_b = +5^\circ$ , $E_b = 0.01$ MV/m	94	98	0.82	45	1.19	0.45/0.25
10	100 uA, $\Delta\phi_b = 0^\circ$ , $E_b = 0.012$ MV/m	97	99.9	1.20	71	1.79	0.65/0.27
11	100 uA, $\Delta\phi_b = 0^\circ$ , $E_b = 0.008$ MV/m	97	86.7	0.68	31	0.82	0.35/0.23

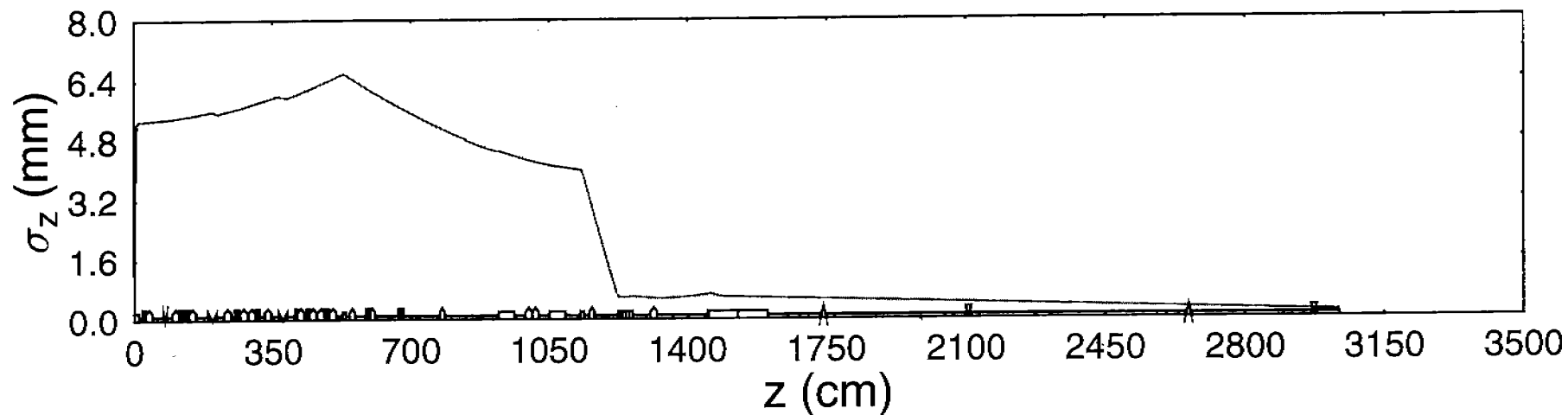
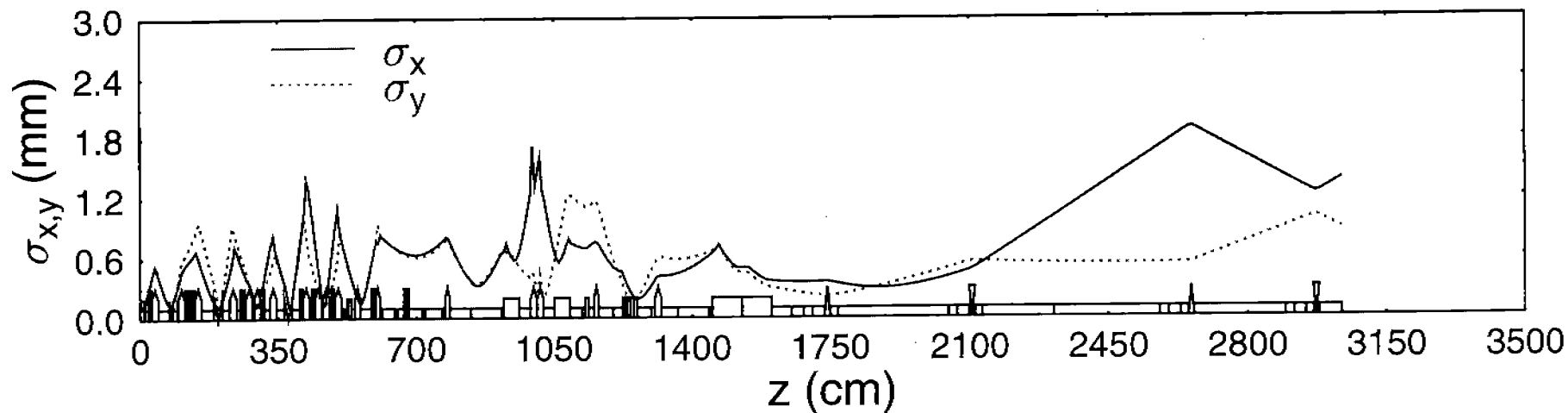
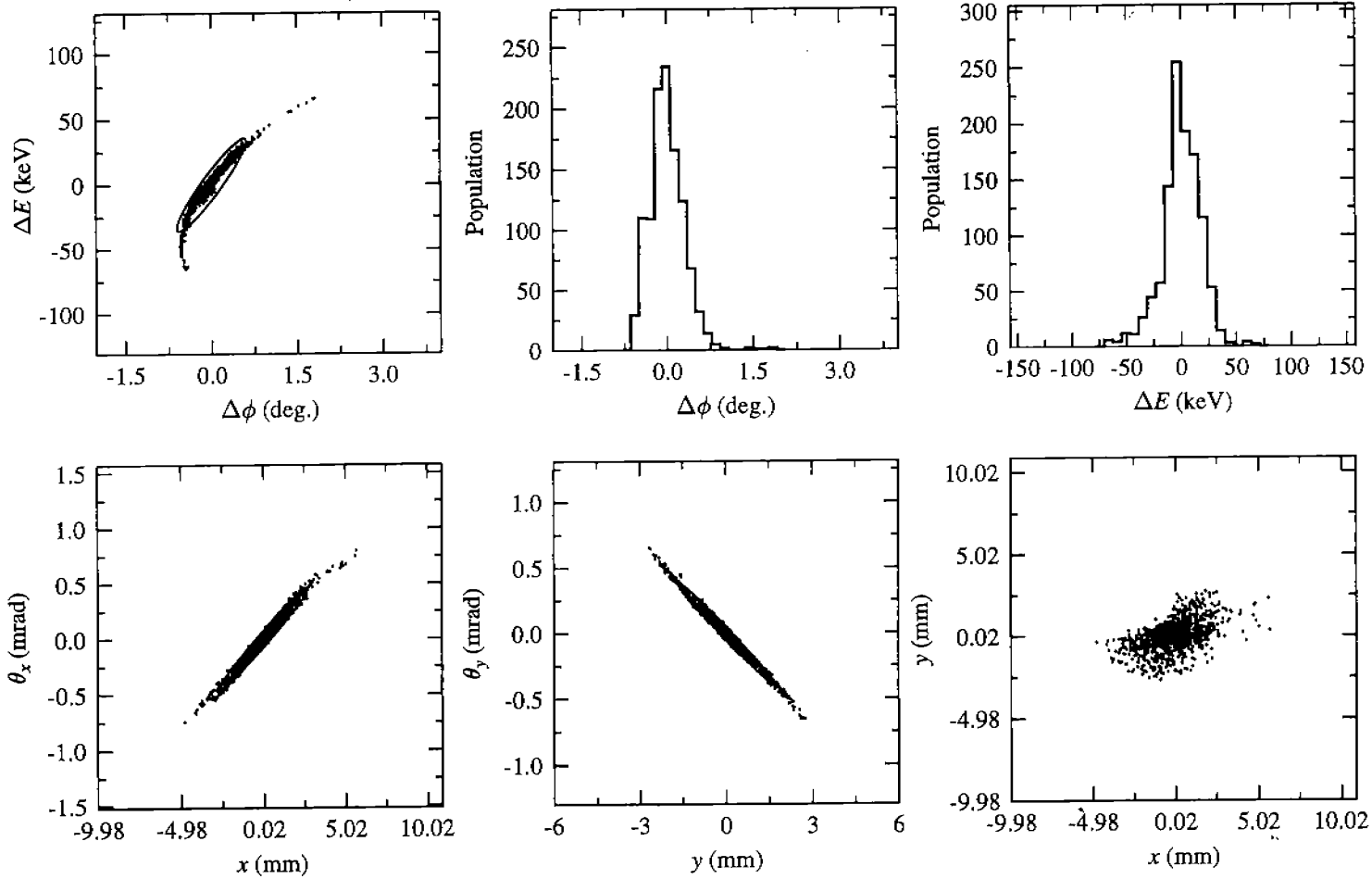


Fig.2 Envelopes of polarized beam (110  $\mu$ A) with  $A_1$ 's diameter = 2 mm and  $A_2$ 's diameter = 4mm, lens 2 moved 10 cm toward BU, additional buncher phased at zero-cross with  $E_0 = 0.0125$  MV/m.

Modeling of polarized beam (Exit # 115;  $N_{\text{good}} = 1116$ )

$E_{\text{beam}} = 5.05273 \text{ MeV}$  ;  $4\sigma_{\phi} = 1.21 \text{ deg.}$  ;  $4\sigma_E = 71.2 \text{ keV}$  ;  $\epsilon_{nz\text{rms}} = 1.82 \text{ deg-keV}$  ;  $f_{56} = -5.544\text{E-}02 \text{ m}$   
 $\epsilon_{nx\text{rms}} = .572 \text{ mm mrad}$  ;  $\sigma_x = 1.3810 \text{ mm}$  ;  $\sigma_{xp} = .235 \text{ mrad}$  ;  $\beta_x = 36.1 \text{ m}$  ;  $\alpha_x = -6.07$   
 $\epsilon_{ny\text{rms}} = .242 \text{ mm mrad}$  ;  $\sigma_y = .88011 \text{ mm}$  ;  $\sigma_{yp} = .205 \text{ mrad}$  ;  $\beta_y = 34.6 \text{ m}$  ;  $\alpha_y = 7.99$



PARMPLOT (c~HL/CEBAF V95.1): 13:46:45 Thu Dec 5 1996 (Plot # 4; z = 3037.973 cm; exit name: Yao 2 )

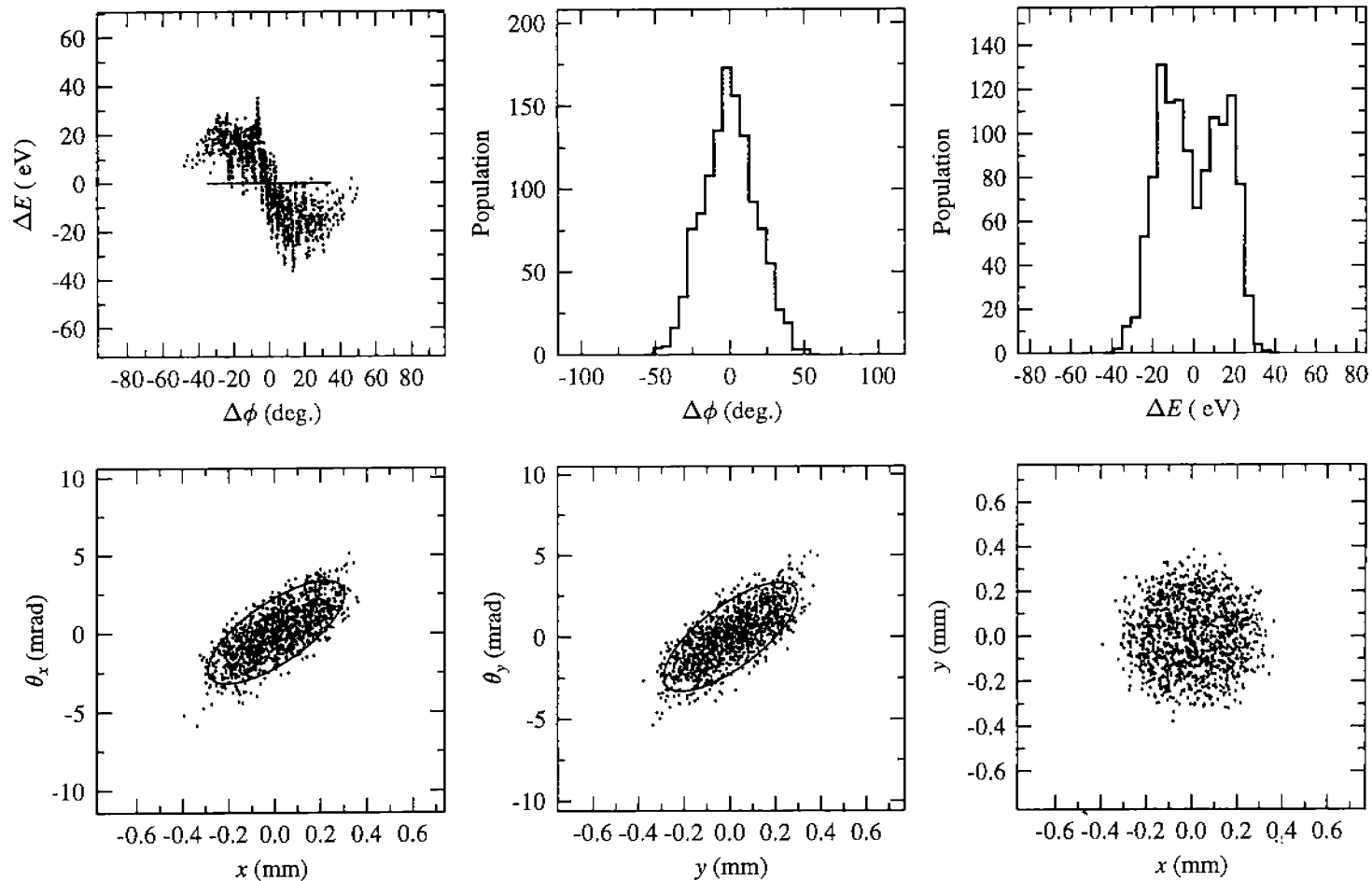
Fig. 3 Distributions of polarized beam at yao 2 ( $I = 110 \mu\text{A}$ )

Modeling of polarized beam (Exit # 1;  $N_{\text{good}} = 1200$ )

$E_{\text{beam}} = 9.996717\text{E-}02$  MeV ;  $4\sigma_{\phi} = 69.9$  deg. ;  $4\sigma_E = 61.2$  eV ;  $\epsilon_{\text{nzrms}} = .172$  deg-keV ;  $f_{56} = 83.6$  m

$\epsilon_{\text{nxrms}} = .109$  mm mrad ;  $\sigma_x = .14819$  mm ;  $\sigma_{xp} = 1.64$  mrad ;  $\beta_x = .132$  m ;  $\alpha_x = -1.06$

$\epsilon_{\text{nyrms}} = .108$  mm mrad ;  $\sigma_y = .14680$  mm ;  $\sigma_{yp} = 1.66$  mrad ;  $\beta_y = .130$  m ;  $\alpha_y = -1.09$



PARMPLOT (c~HL/CEBAF V95.1): 14:28:34 Thu Dec 5 1996 (Plot # 1;  $z = 11.748$  cm; exit name: Gun + )

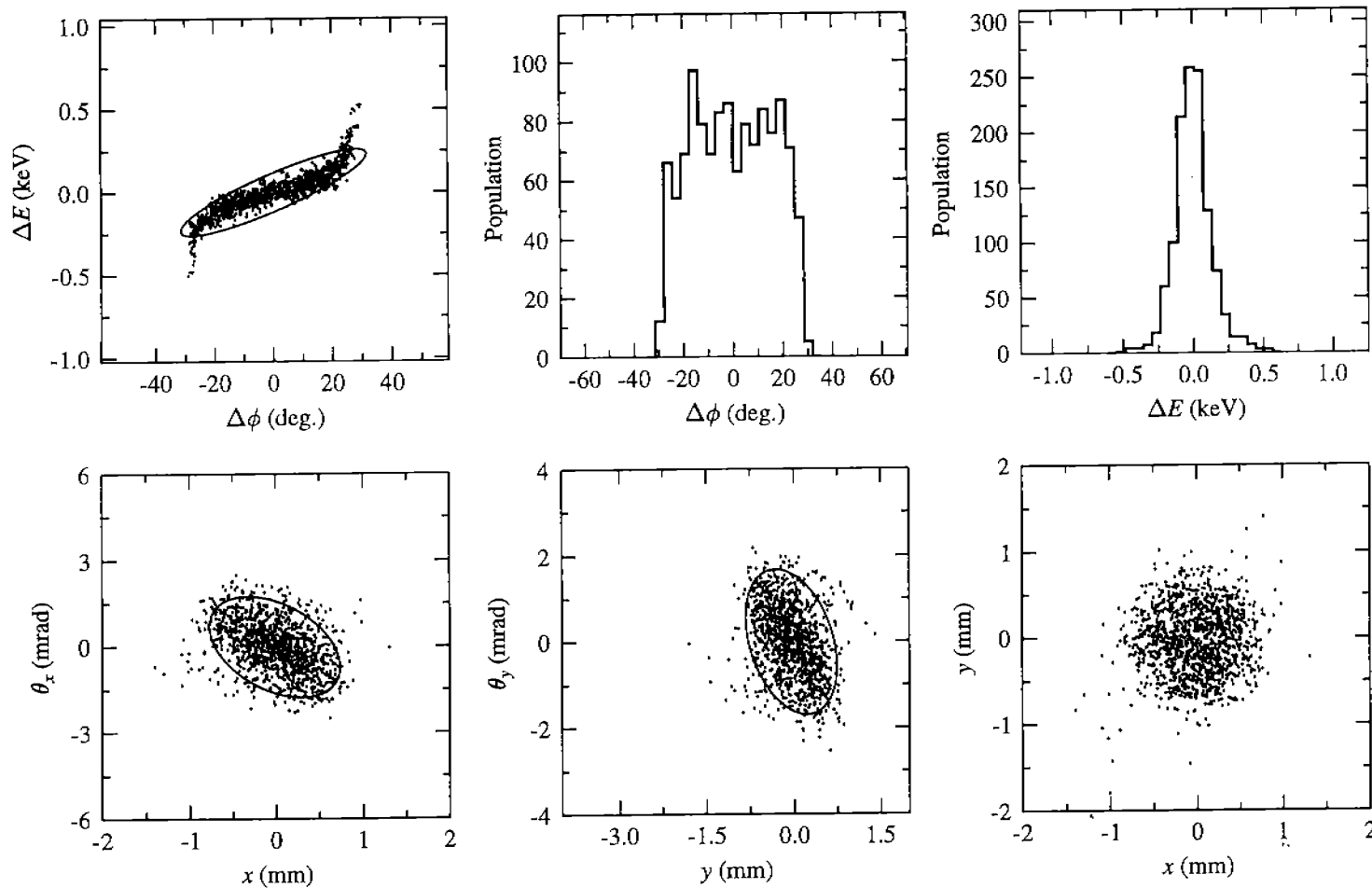
Fig. 4 Distributions of polarized beam at gun exit ( $I = 110$   $\mu$ A).

Modeling of polarized beam (Exit # 58;  $N_{\text{good}} = 1200$ )

$E_{\text{beam}} = 9.996969\text{E-}02$  MeV ;  $4\sigma_{\phi} = 63.2$  deg. ;  $4\sigma_E = .521$  keV ;  $\epsilon_{nz\text{rms}} = .939$  deg-keV ;  $f_{56} = -7.63$  m

$\epsilon_{nx\text{rms}} = .199$  mm mrad ;  $\sigma_x = .37799$  mm ;  $\sigma_{xp} = .879$  mrad ;  $\beta_x = .471$  m ;  $\alpha_x = .447$

$\epsilon_{ny\text{rms}} = .204$  mm mrad ;  $\sigma_y = .39214$  mm ;  $\sigma_{yp} = .845$  mrad ;  $\beta_y = .494$  m ;  $\alpha_y = .362$



PARMPLOT (c~HL/CEBAF V95.1): 14:28:48 Thu Dec 5 1996 (Plot # 2; z = 838.149 cm; exit name: A1 -)

Fig. 5 Distributions of polarized beam at entrance to A1 ( $I = 110$   $\mu\text{A}$ ).

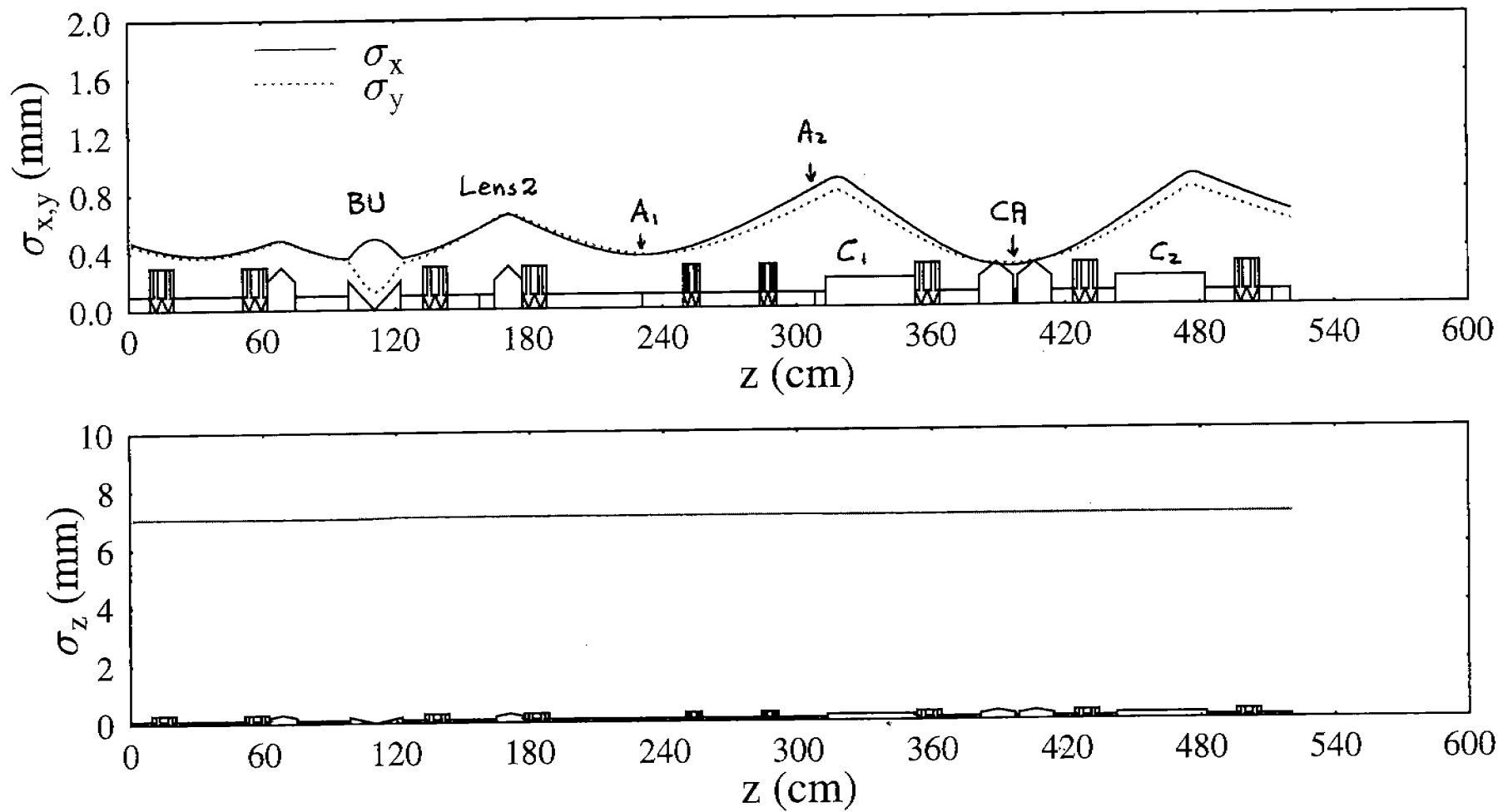


Fig. 6 Envelopes of thermionic beam with both chopper cavities turned off.