

# EMITTANCE MEASUREMENTS AT THE A0 PHOTO-INJECTOR

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## Abstract

The A0 photo-injector produces electron bunches of 1–14 nC charge with an energy of 18 MeV. Detailed measurements and optimization of emittance have been carried out for a number of gun and laser operating conditions, beam line optics conditions, and at a number of beam line locations. Results are compared with the predictions of simulations using HOMDYN.

## 1 INTRODUCTION

The photo-injector consists of a 1.625-cell RF gun resonating in the  $TM_{010,\pi}$  mode at 1.3 GHz. The gun contains a high quantum efficiency  $Cs_2Te$  photocathode. The UV light is provided by a pulsed Nd:YLF laser. To confine the space charge dominated beam, three solenoids (a primary, a secondary and a bucking to zero the magnetic field on the cathode) are installed around the gun and the beam is accelerated by a 9-cell superconducting cavity upon exiting the gun. After the 9-cell, a magnetic chicane composed of four dipoles allows longitudinal compression of the beam. A quadrupole doublet and three quadrupole triplets are used to transport the beam to a spectrometer at the end of the beam line ( $z \cong 11.2$  m).

The predicted performance of the photo-injector is presented in [1]. For the measurements presented in this paper, the RF gun's pulse length was 30  $\mu s$ , the repetition rate was 1 Hz, and a train of 10 bunches was used, with charge up to 12 nC per bunch. The longitudinal distribution of the laser pulse had  $\sigma_t = 4.6$  ps, as measured with a streak camera. The 9-cell was operated with a useful pulse length of 100  $\mu s$ , an accelerating field of 12 MV/m and 10° off crest to minimize the energy spread. For a peak RF field at the cathode of  $E_0 = 40$  MV/m and a launch phase of  $\phi_0 = 40^\circ$  to maximize the energy at the exit of the gun, the total energy  $E_t$  and the relative energy spread  $\delta$  of a 1 nC uncompressed beam were then measured at  $E_t = 18.2$  MeV and  $\delta = 0.25\% \pm 0.02\%$ , in agreement with the HOMDYN [2] simulation, which gives  $E_t = 17.8$  MeV and  $\delta = 0.25\%$ . In the following,  $Q$  is the charge per bunch,  $\sigma$  is the rms size ( $x$  or  $y$ ) of the laser beam on the cathode, and  $I_{sol}$  is the current in the solenoids. The three solenoids were used with the same current, implying a non-zero magnetic field on the cathode ( $< 7$  mT) and a residual magnetic normalized emittance [3]  $\epsilon_{n,rms}^{mag} \lesssim 2\sigma^2$ . Due to the saturation of the primary and bucking solenoids, the maximum axial magnetic field  $B_z^{max}$  produced by the three solenoids presents a non-linear dependence w.r.t. the current above

130 A: for  $I_{sol} = 130$  A,  $B_z^{max} = 77.5$  mT and for  $I_{sol} = 260$  A,  $B_z^{max} = 132.5$  mT.

## 2 MEASUREMENT PRINCIPLE

The emittance measurements were done using the slit technique: five actuator-mounted slit masks allow the measurement of the vertical emittance  $\epsilon_y$  at  $z = 3.7$  m, and of both  $\epsilon_x$  and  $\epsilon_y$  at  $z = 6.5$  m and  $z = 9.6$  m. The beamlets passing through the slits are viewed with optical transition radiation (OTR) screens located at a distance  $d = 384$  mm,  $d = 1122$  mm,  $d = 380$  mm from the slits, respectively. The masks consist of 6 mm thick tungsten slats with 50  $\mu m$  wide slits spaced 1 mm apart. As presented in [4], we first used a Matlab program to analyze each of the slit image and compute the rms normalized emittance as given by HOMDYN and defined by [5] as:

$$\epsilon_{n,u} = \beta\gamma \sqrt{\langle u^2 \rangle \langle (u')^2 \rangle - \langle uu' \rangle^2} \quad (1)$$

where  $u$  represents the transverse coordinate  $x$  or  $y$ ,  $\beta c$  is the velocity of the beam, and  $\gamma$  is the Lorentz factor. This method gave poor resolution (underestimating the emittance) if the slits images were not clearly defined, which was often the case in the measurements we made while varying the photo-injector parameters. We then decided to compute the emittance using

$$\epsilon_{n,u} = \beta\gamma\sigma_u\sigma'_{u,slit} \quad (2)$$

where  $\sigma_u$  is the rms size of the beam at the slit location and  $\sigma'_{u,slit}$  is the divergence of the beam measured as the ratio of one slit rms size divided by the distance  $d$  between the slits mask and the OTR screen. A Gaussian fit was used to obtain  $\sigma_u$  and  $\sigma'_{u,slit}$ . All the results presented in this paper were obtained using the definition (2).

## 3 OPTIMIZATION OF THE EMITTANCE AT THE EXIT OF THE 9-CELL

All the measurements in this section were made at  $z = 3.7$  m, which is at the exit of the 9-cell.

### 3.1 Launch phase

Figure 1 shows  $\epsilon_y$  as a function of the gun launch phase  $\phi_0$  with  $Q = 1$  nC,  $E_0 = 40$  MV/m and  $\sigma = 0.7$  mm. For each value of  $\phi_0$ , we measured  $\epsilon_y$  as a function of the solenoid current, and we show minimum values in Figure 1. Three régimes can be seen: for  $\phi_0 < 30^\circ$ , we had to increase the laser energy to keep a 1 nC beam, and then the emittance increased; for  $\phi_0 > 60^\circ$ , the energy of the beam at the exit of the gun was too low to allow a correct transport to the spectrometer; for  $30^\circ < \phi_0 < 60^\circ$ , the emittance

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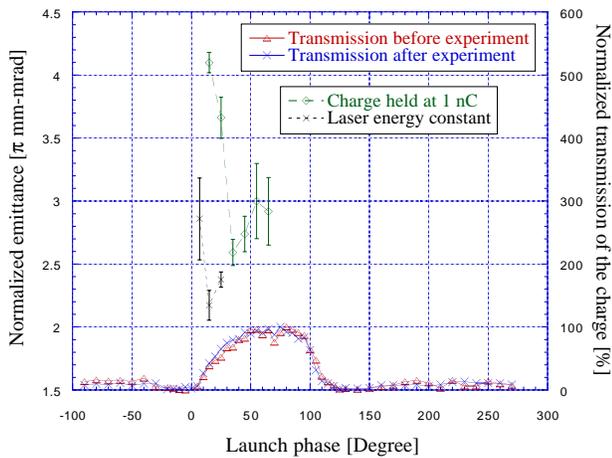


Figure 1. Normalized emittance of a 1 nC beam versus gun launch phase.

was nearly constant, between 2.8 and 3  $\pi$ mm mrad. Thus, we do not see an ideal phase that lowers significantly the emittance, but rather a region ( $30^\circ < \phi_0 < 60^\circ$ ) for which the emittance is low. In the following experiments, we have chosen  $\phi_0 = 40^\circ$ .

### 3.2 Field on the gun

Figure 2 shows  $\epsilon_y$  as a function of the solenoid current for 1 and 8 nC and  $E_0 = 30, 35, \text{ and } 40$  MV/m. In all cases,  $\phi_0 = 40^\circ$ ; for Figure 2a,  $\sigma = 0.8$  mm; for Figure (2b),  $\sigma = 1.5$  mm. We can see that the emittance of a 1 and 8 nC beam at the exit of the 9-cell can be kept at the same minimum value for  $E_0 = 30, 35, \text{ and } 40$  MV/m, but at the price of delicate tuning of the solenoid field while lowering  $E_0$ . Operating the RF gun at  $E_0 = 30$  MV/m presents the advantage of producing 4 times less dark current ( $\sim 0.9$  mA) than at  $E_0 = 40$  MV/m. Due to the fact that the dark current has never been a problem at A0, we did most of the emittance measurements at  $E_0 = 40$  MV/m.

### 3.3 Charge

Figure 3 shows  $\epsilon_y$  as a function of charge. Measurements were done for  $Q = 1, 4, 6, 8, \text{ and } 12$  nC,  $\phi_0 = 40^\circ$ , and  $E_0 = 40$  MV/m. For each charge, we measured the emittance for three different values of the laser spot size  $\sigma$  on the cathode and as a function of the solenoid current. Figure 4 shows the measurements at 1 and 4 nC, and Figure 5 shows the optimum case of 8 nC ( $\sigma = 1.5$  mm), in good agreement with the HOMDYN simulation. The values shown in Figure 3 are the minima relative to  $\sigma$  and  $I_{sol}$ . Thus, the optimized emittance measured at the exit of the injector has a linear dependence on the charge and agrees with the HOMDYN simulation.

## 4 EMITTANCE ALONG THE BEAM LINE

Table 1 shows the emittance of a 1 nC and 8 nC beam measured in three locations along the beam line and compared with the HOMDYN simulations. We used the parameters

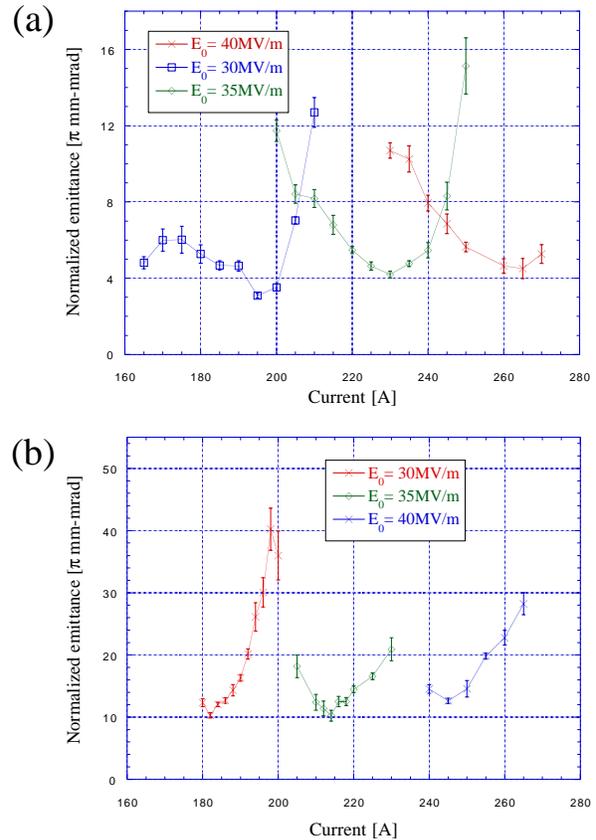


Figure 2. Measurement of the emittance at the exit of the 9-cell for (a) 1nC and (b) 8nC versus current in the solenoids for three values of  $E_0$ .

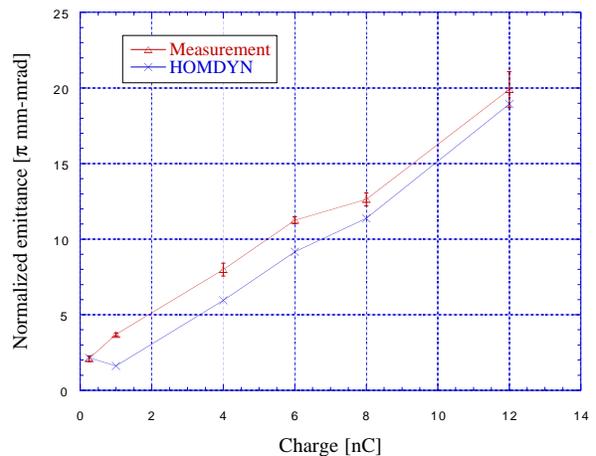


Figure 3. Minimum normalized emittance at the exit of the 9-cell versus the charge per bunch.

of the RF gun and the 9-cell that gave the minimum emittance at the exit of the 9-cell, as indicated in Figure 3.

For the 1 nC case:  $\sigma = 0.8$  mm,  $I_{sol} = 260$  A, and we used the first triplet ( $z = 6.1\text{--}6.4$  m) to optimize the transport until the end of the spectrometer. For the 8 nC case:  $\sigma = 1.5$  mm,  $I_{sol} = 245$  A, and we used the first and second triplets ( $z = 7.8\text{--}8.1$  m) for the transport.

Table 1 shows that the emittance of a 1 and 8 nC beam

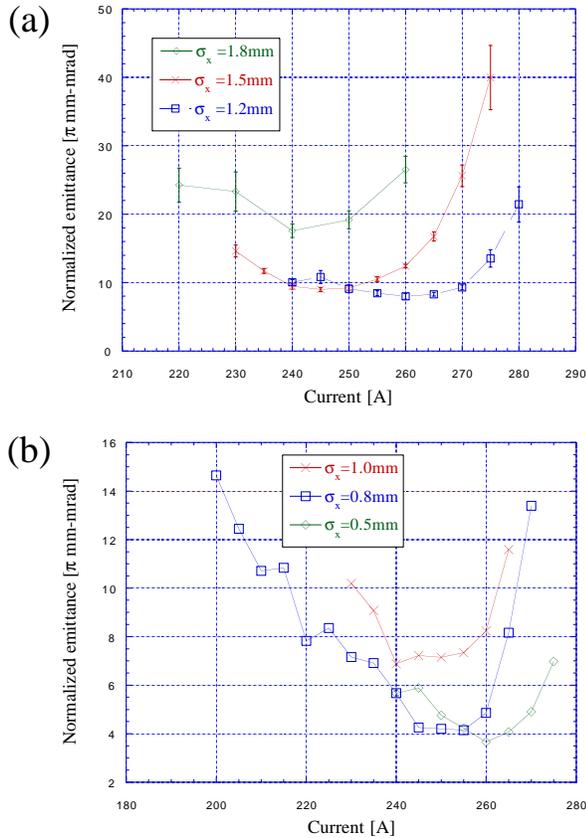


Figure 4. Measurement of the emittance at the exit of the 9-cell for (a) 1 nC and (b) 4 nC versus current in the solenoids for three transverse rms sizes of the laser beam.

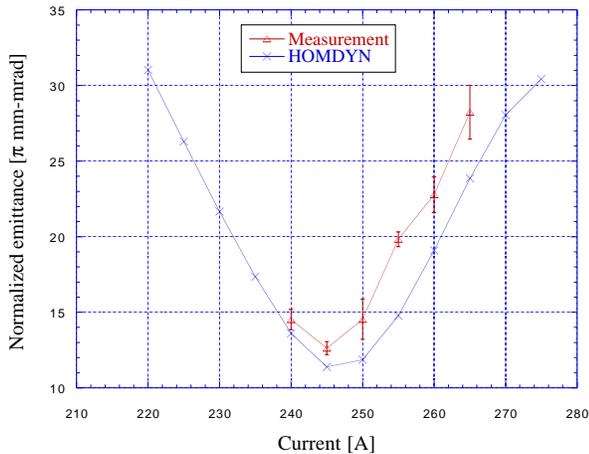


Figure 5. Normalized emittance of a 8 nC beam versus current in the solenoids.

Table 1. Emittance measurements at 1nC and 8nC for different locations along the beam line, with comparison to HOMDYN simulations.

Item	z [m]	Emittance [ $\pi$ mm mrad]			
		$Q = 1$ nC		$Q = 8$ nC	
		Meas	Sim	Meas	Sim
$\epsilon_y$	3.7	$3.7 \pm 0.1$	1.7	$10.0 \pm 0.1$	11.4
$\epsilon_x$	6.5	$5.0 \pm 0.2$	1.5	$11.6 \pm 0.5$	12.2
$\epsilon_y$	6.5	$5.1 \pm 0.2$	1.5	$8.9 \pm 0.7$	11.6
$\epsilon_x$	9.7	$6.8 \pm 0.2$	1.0	$14.4 \pm 0.5$	11.5
$\epsilon_y$	9.7	$5.8 \pm 0.2$	1.1	$18.3 \pm 0.9$	12.4

remains stable along the beam line. We can see also from this table that the measured emittance of a 8 nC beam is in good agreement with HOMDYN, but this is not true in the 1 nC case. Measurements of the beam envelope through the beam line [6] also show good agreement with HOMDYN at 8 nC but not at 1 nC. Work is in progress to understand the disagreement with HOMDYN.

## 5 CONCLUSION

We have determined the parameters of the photo-injector to produce and transport a low emittance beam with a charge of up to 12 nC. The vertical emittance has been measured at the exit of the 9-cell ( $z = 3.7$  m) at  $\epsilon_y = 3.7 \pm 0.1$   $\pi$ mm mrad and  $\epsilon_y = 19.9 \pm 1.2$   $\pi$ mm mrad, for a charge of 1 and 12 nC respectively. The emittance measurements show a good agreement with HOMDYN for a high charge but not for a low one ( $<4$  nC).

## REFERENCES

- [1] D. A. Edwards, Ed., “TeSLA Test Facility Linac—Design Report,” DESY Report TeSLA-95-01 (March 1995).
- [2] M. Ferrario *et al.*, *Particle Accelerators* **52** (1996), pp. 1–30.
- [3] S. Nagaitsev and A. Shemyakin, “Beam emittance calculation in the presence of an axially symmetric magnetic field”, Fermilab Report TM-2107 (May 2000).
- [4] J.-P. Carneiro *et al.*, “Beam dynamics studies in a high-brightness photo-injector,” Proceedings of the FEL99 conference, DESY, Hamburg, 1999.
- [5] P. M. Lapostolle, *IEEE Trans. Nucl. Sci.* **NS-18** (1971), pp. 1101–1104.
- [6] J.-P. Carneiro, “Etude expérimentale du photo-injecteur de Fermilab”, Ph.D. Thesis, Université Paris XI, 2000, to be published.