Note LAL-SERA-2000-130

Design Studies for a High Current Bunching System for CLIC Test Facility (CTF3) Drive Beam

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Contents

Introduction

CLIC is a two beam accelerator (TBA) based e^+e^- linear collider. As other linear collider projects, such as NLC, JLC, and TESLA, CLIC evolves in terms of its conceptions and technologies. The recently proposed CLIC drive beam scheme makes CLIC more interesting [1]. To demonstrate the feasibility of the new drive beam scheme and to test other technical aspects, CTF3 [2] has been proposed as a natural successor of the existing CTF2 to which LAL has actively collaberated and contributed in the past years [3][4]. In this talk we will restrict ourselves to the study of the bunching system for CTF3 which is a new subject of collaboration between LAL and CLIC group of CERN.
The design consists of choosing bunching system layout, parameters, and numerical simulations. In the following sections we will discuss the design of the travelling wave buncher considering the beam loading effect, the numerical simulations of the proposed bunching systems by using PARMELA, the multibunch longitudinal and transverse beam dynamics in the TW buncher with the presence of long range wakefields, and discussions on the analytical HOM coupler design.

Beam loading effect

We start with the power diffusion equation in a linac

$$\frac{dP(z)}{dz} = -2\alpha(z)P(z) - IE(z) \tag{1}$$

where $P(z)$ is the power flow inside the structure, $E(z)$ is the amplitude of the synchronous accelerating field which can be decomposed into two parts, $E(z) = E_{rf}(z) - E_b(z)$, with $E_{rf}(z)$ and $E_b(z)$ being the applied rf field and the beam induced field, respectively, and I is the average beam current during the rf pulse. By using the following equations

$$\frac{dP(z)}{dz} = \frac{E(z)}{\alpha(z)R_{sh}(z)}\frac{dE(z)}{dz} \tag{2}$$

$$2\alpha(z)P(z) = \frac{E(z)^2}{R_{sh}(z)} \tag{3}$$

one gets from eq. 1:

$$\frac{dE(z)}{dz} = -\alpha(z)E(z) - \alpha(z)IR_{sh}(z) \tag{4}$$

where $R_{sh}(z)$ is the shunt impedance of the accelerating mode. Now we decompose eq. 4 into two equations:

$$\frac{dE_{rf}(z)}{dz} = -\alpha(z)E_{rf}(z) \tag{5}$$

and

$$\frac{dE_b(z)}{dz} = -\alpha(z)E_b(z) + \alpha(z)IR_{sh}(z) \tag{6}$$

If $R_{sh}(z)$ and $\alpha(z)$ are kept constant within the accelerating structure, by using the initial condition $E_{rf}(0) = E_0$ and $E_b(0) = 0$, one gets from eq. 5 and 6:

$$E_{rf}(z) = E_0 \exp(-\alpha z) \tag{7}$$

$$E_b(z) = IR_{sh}(1 - \exp(-\alpha z)) \tag{8}$$

and

$$E(z) = E_{rf}(z) - E_b(z) = E_0 \exp(-\alpha z) - IR_{sh}(1 - \exp(-\alpha z)) \tag{9}$$

where $E_0 = \sqrt{2\alpha P_0 R_{sh}}$ and P_0 is the input power from the rf source. $E_b(z)$ is the stationary electric field distribution due to beam loading effect. When the particle is not situated on the crest of E_{rf}, the real field seen by the particle is

$$E(z) = E_0 \exp(-\alpha z) \sin(\phi) - IR_{sh}(1 - \exp(-\alpha z)) \tag{10}$$

where $\phi = \pi/2$ corresponds to the maximum acceleration, and this expression was first obtained by A.J. Lichtenberg [5].
To have good energy transfer efficiency and energy gain at the same time, one requires:

$$E(L) = 0 \tag{11}$$

where L is the length of the accelerating section. When the ohm loss on the structure wall is small the fully beam loaded condition results in

$$P_0 = \frac{IE_0L}{2} \tag{12}$$

For a given E_0, I, and L, one gets P_0 from eq. 12 and one can determine the geometry of the disk-loaded structure by solving the following equations:

$$\frac{E_0^2}{P_0} = \frac{\omega R_{sh}}{v_g Q} = \frac{4k_{010}}{c(v_g/c)} \tag{13}$$

where k_{010} and v_g/c can be expressed analytically as [6][7]:

$$k_{010} = \frac{2J_0^2\left(\frac{u_{01}}{R}a\right)\sin^2\left(\frac{u_{01}h}{2R}\right)}{\epsilon_0 \pi h D J_1^2(u_{01}) u_{01}^2} \tag{14}$$

$$K_e = \frac{4a^3}{3\pi h R^2 J_1^2(u_{01})} \exp(-\alpha_e d) \tag{15}$$

$$\frac{v_g}{c} = \frac{\omega K_e D \sin(\theta_0)}{2c} \tag{16}$$

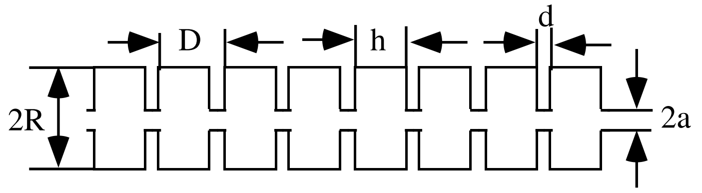


Figure 1: Disk-loaded accelerating structure

$$\alpha_e = \left((2.405/a)^2 - (2\pi/\lambda)^2\right)^{1/2} \tag{17}$$

where the definitions of a, h, R, D, and d are given in Fig. 1. For example, taking $E_0 = 15$ MV/m, $I = 3.5$ A, $L = 1.3$ m, one finds $P_0 = 34$ MW, $a = 0.0141$ m, $h = 0.028$ m, $R = 0.04$ m, $D = 0.033$ m, $v_g/c = 0.038$, $k_{010} = 19$ V/pC/m of a constant impedance linac working at 3 GHz and $2\pi/3$ mode (like CLIC fully beam loaded structure). Now we make a rough design for the TW buncher. First of all we determine the structure geometry of the region of $\beta = 1$. If one takes $E_0 = 10$ MV/m, $R = 0.04$ m, $I = 4$ A, $L = 0.8$ m, one finds $P_0 = 16$ MW, $a = 0.016$ m, $h = 0.02$ m, $D = 0.033$ m, $v_g/c = 0.029$, $k_{010} = 13.7$ V/pC/m of a constant impedance linac working at 3 GHz and $2\pi/3$ mode. The geometry of the region of $\beta = 0.75$ has been chosen according to the criteria that the power flow between the two distinct region should be continuous and that the field levels at the entrances of the two distinct structures should be the same for the same input power. The dimensions of the cells with $\beta = 0.75$ have been found as $a = 0.01455$ m, $h = 0.0137$ m, $D = 0.025$ m, and $v_g/c = 0.031$ with $k_{010} = 14.6$ V/pC/m. The disk thickness between the cells of $\beta = 0.75$ and $\beta = 1$ is 0.013 m and the iris radius of this intermediate disk is 0.0152 m. In summary, the dimensions of the TW buncher is given in Table 1.

Cell type	D (m)	h (m)	a (m)	v_g	k_{010} (V/pC/m)
$\beta = 0.75$	0.025(m)	0.0137 (m)	0.0146 (m)	0.031	14.56
$\beta = 1$	0.033 (m)	0.02 (m)	0.016 (m)	0.029	13.7

Table 1: summary of TW buncher dimension

Numerical simulation of the bunching systems

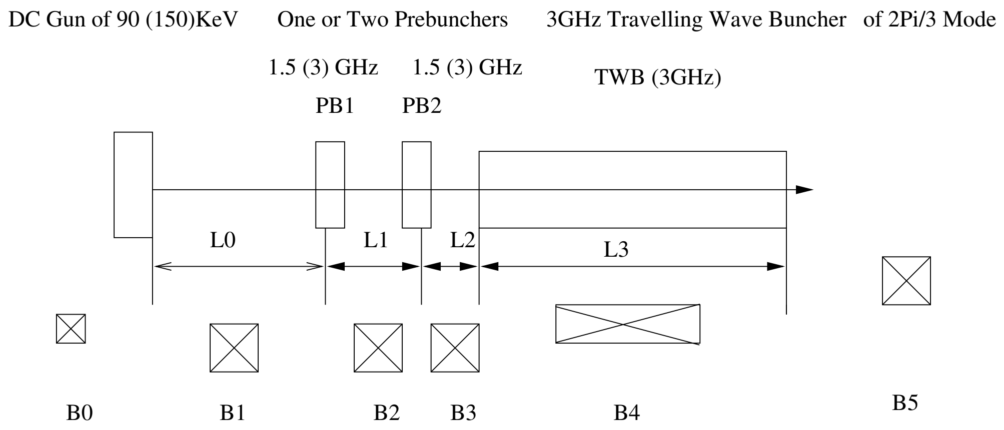
The design goal [8][9] of CTF3 is listed below:

CTF3 Design Goal

Beam energy at the exit of the injector	~26 MeV
Pulse length	1.6 us
Beam current per pulse	3.5 A
Charge per pulse	1.17-2.33 nC
Bunch spacing	10-20 cm
Bunch length (FWHH and rms)	<12 ps and 5 ps
Normalized emittance	<100 mm.mrad
Single bunch uncorrelated energy spread (rms)	<0.5 MeV
Pulse repetition frequency	5 Hz
Allowed charge in satallite	< 5%

Figure 2: The injector design goal.

Bunching Systems Proposed for CFT3



TWB: 3 cells of phase velocity =0.75c and 21 cells of phase velocity =c, E0=10MV/m (at the input coupler), L3=0.8m

For two 3 GHz prebunchers case: L0=50 cm, L1=15 cm, and L2=10 cm

For one 1.5 GHz and one 3 GHz prebuncher case: L0=50 cm, L1=15 cm, and L2=10 cm

For one 1.5 GHz prebuncher case: the prebuncher is located at L0=50 cm and L1+L2=25 cm

For two 1.5 GHz prebunchers case: L0=50 cm, L1=22 cm, and L2=3 cm

Figure 3: Bunching systems proposed for CTF3.

Figure 4: Two 3GHz prebuncher case with DC gun of 90 KV.

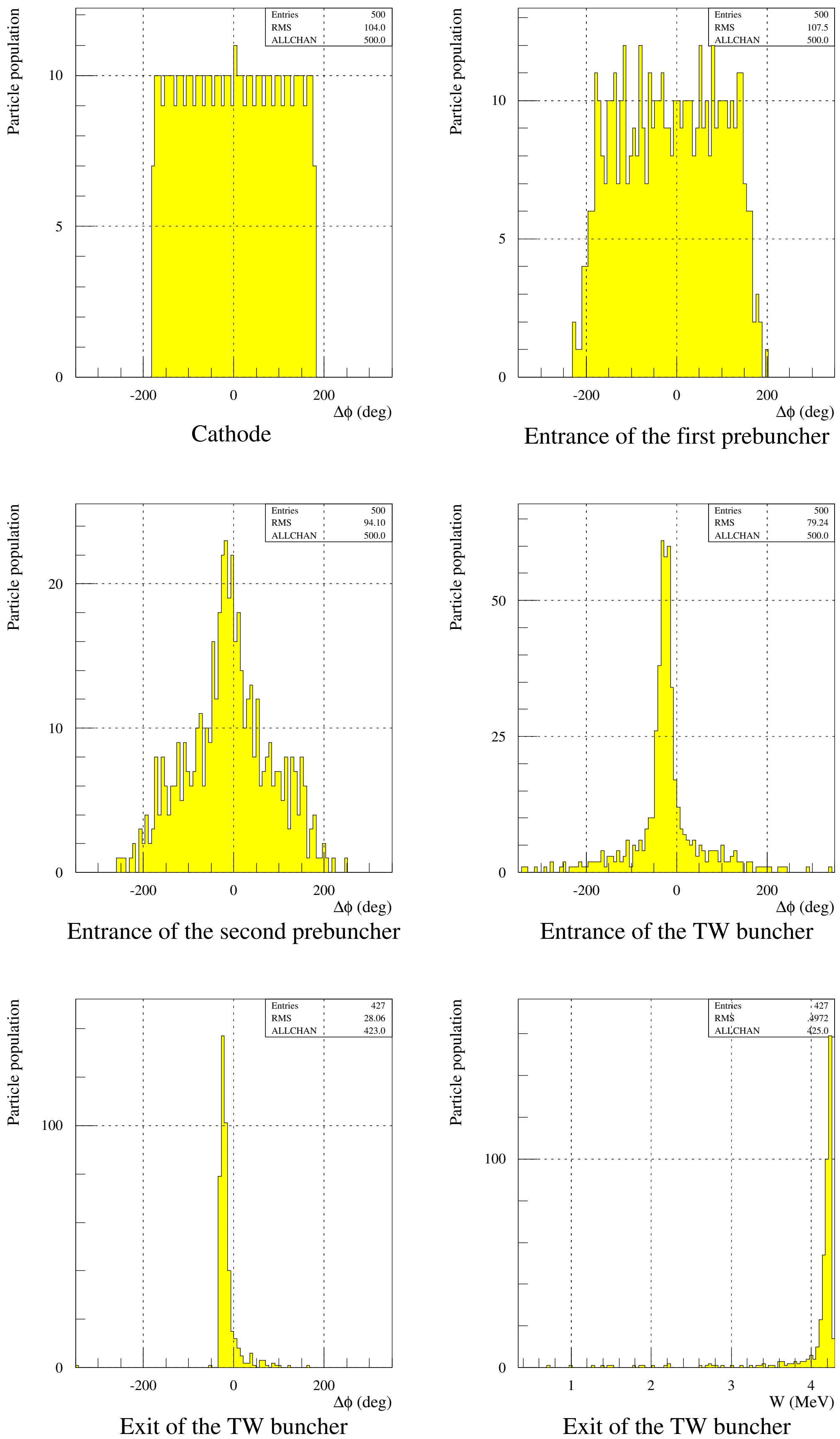
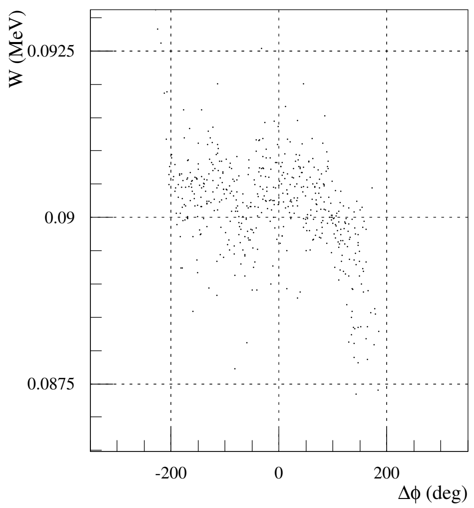
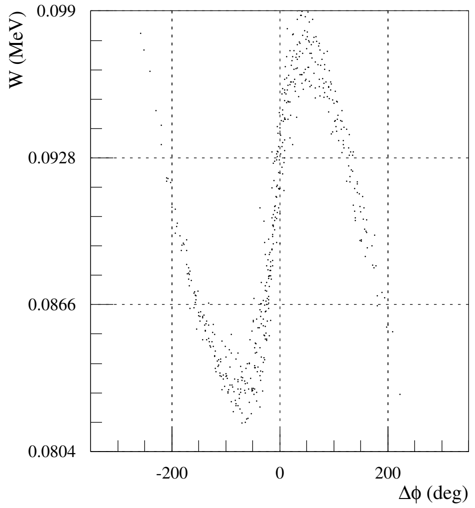


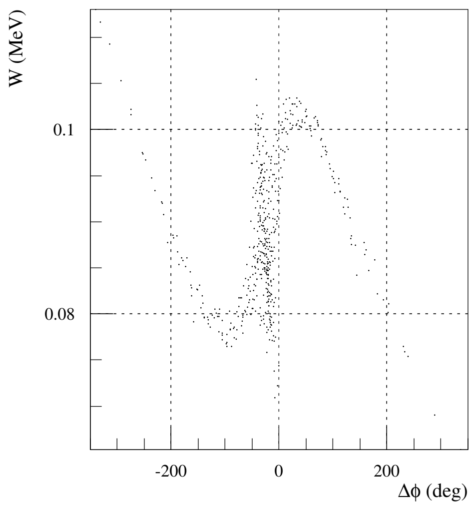
Figure 5: Two 3GHz prebuncher case with DC gun of 90 KV.



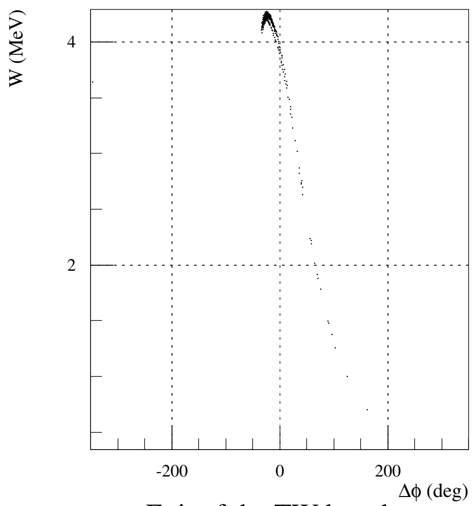
Entrance of the first prebuncher



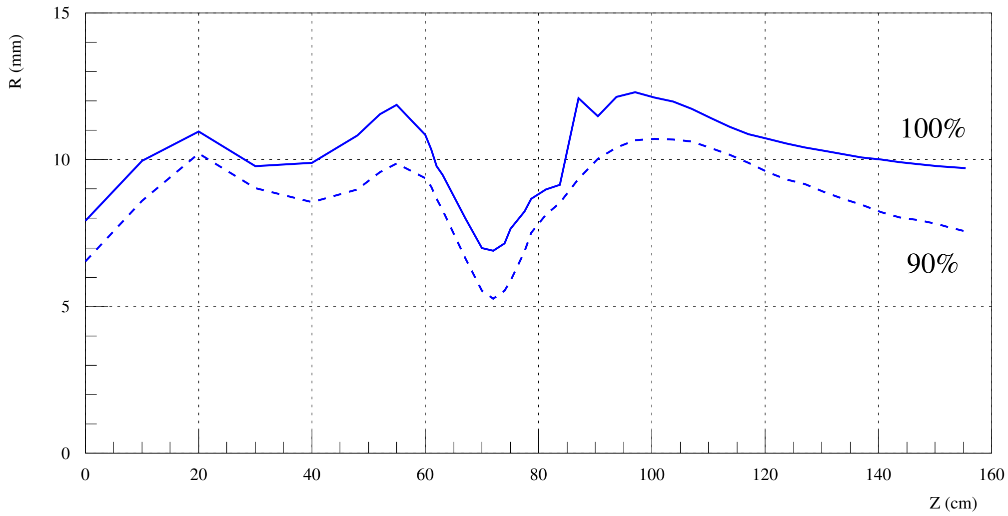
Entrance of the second prebuncher



Entrance of the TW buncher



Exit of the TW buncher



Beam envelope

Figure 6: Two 3GHz prebuncher case with DC gun of 90 KV.

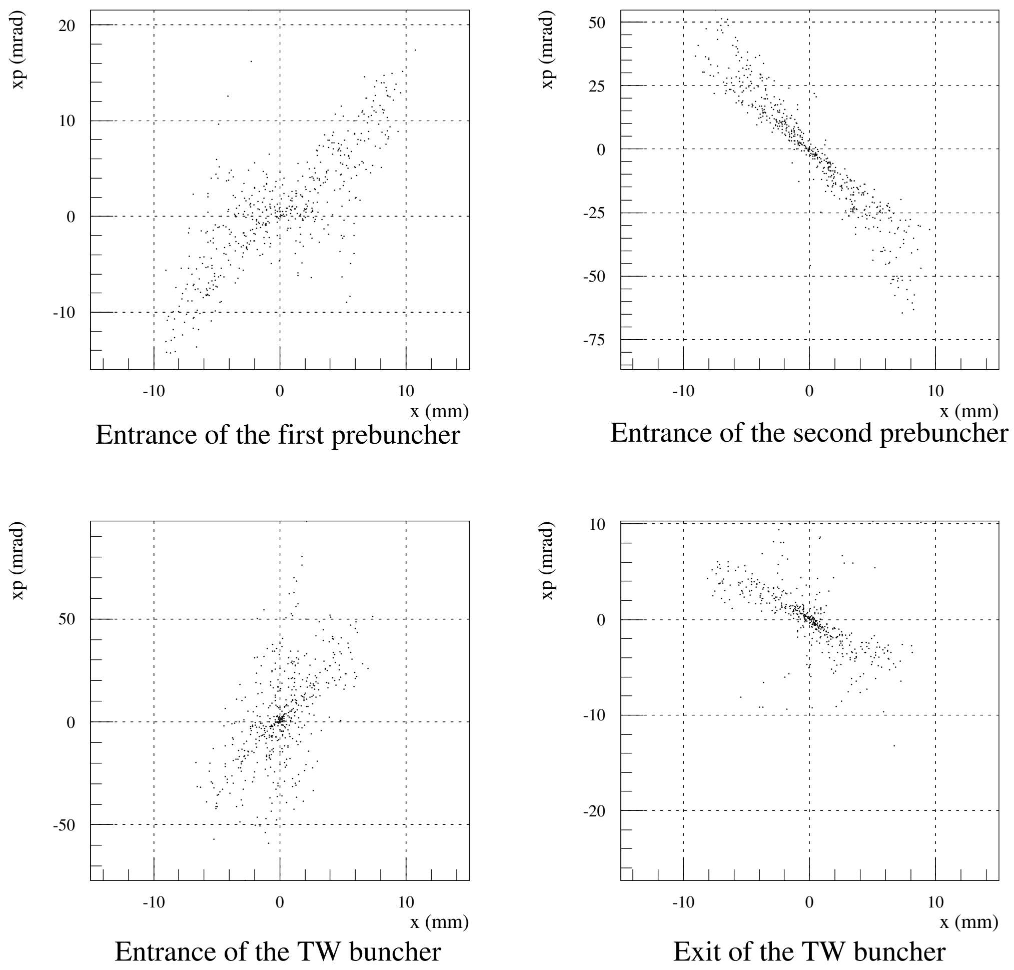


Figure 7: Two 3GHz prebuncher case with DC gun of 90 KV.

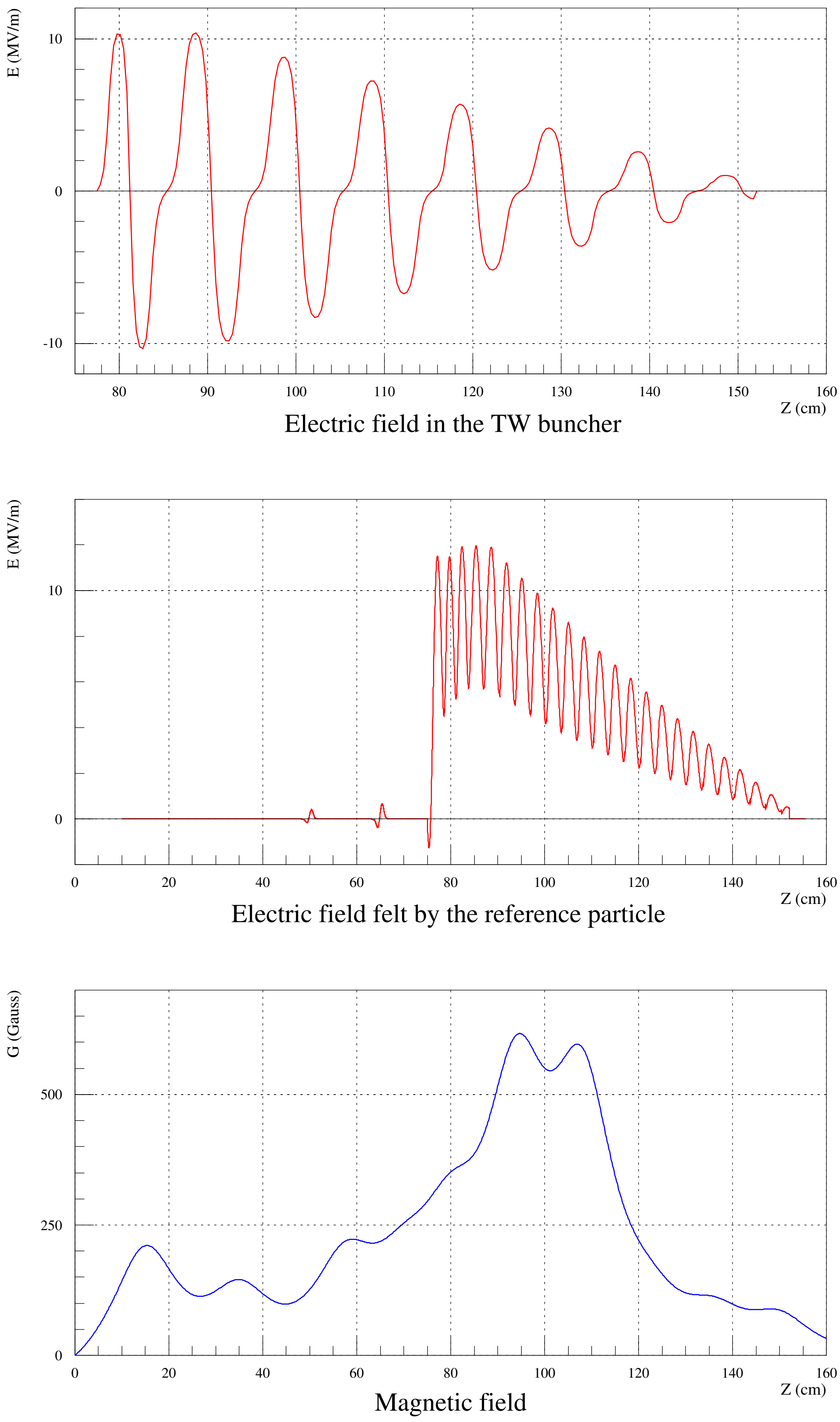


Figure 8: Two 3GHz prebuncher case with DC gun of 90 KV.

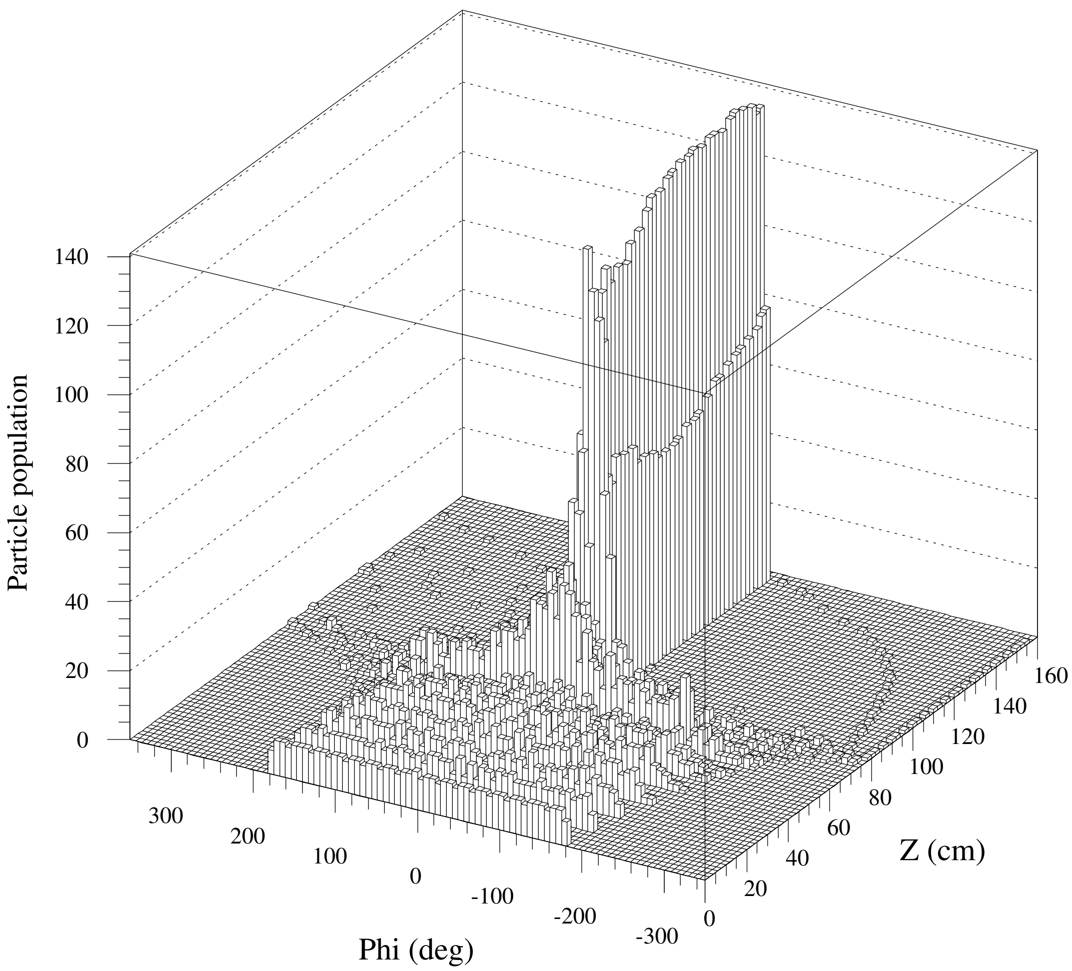
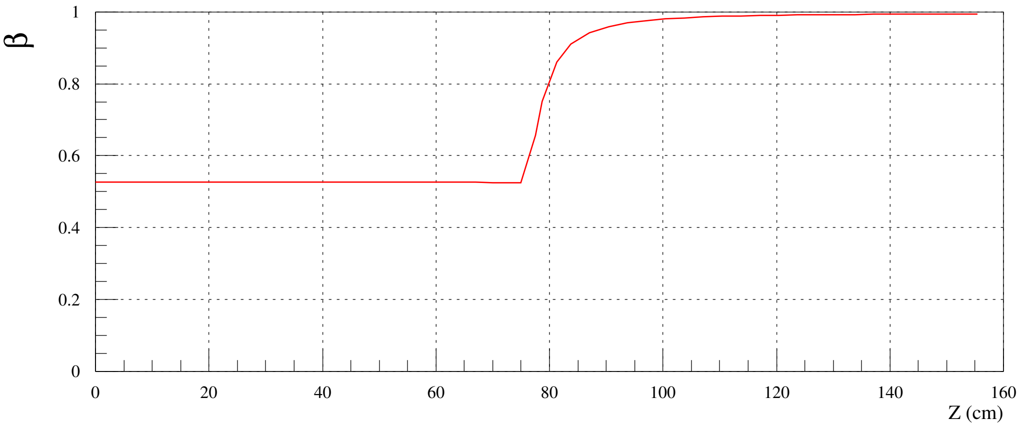
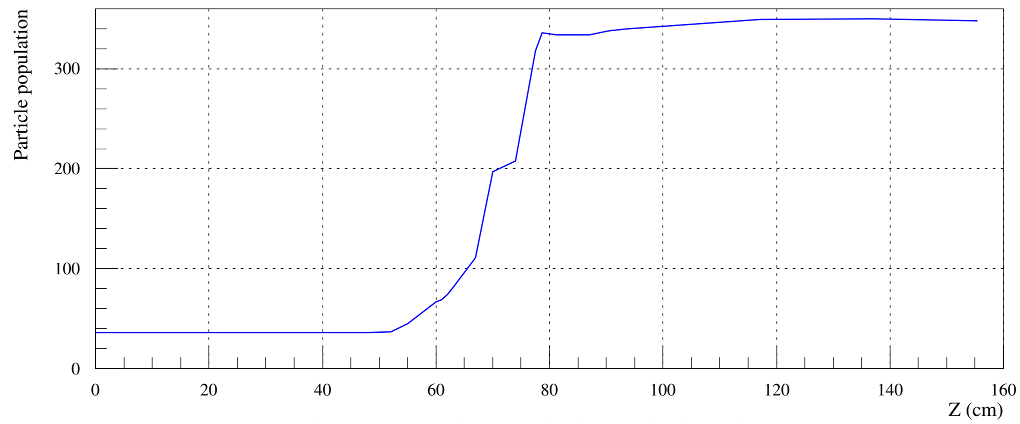


Figure 9: Two 3GHz prebuncher case with DC gun of 90 KV.



Velocity variation in the bunching system



Particle population variation within 26 degree

Figure 10: Two 3GHz prebuncher case with DC gun of 150 KV.

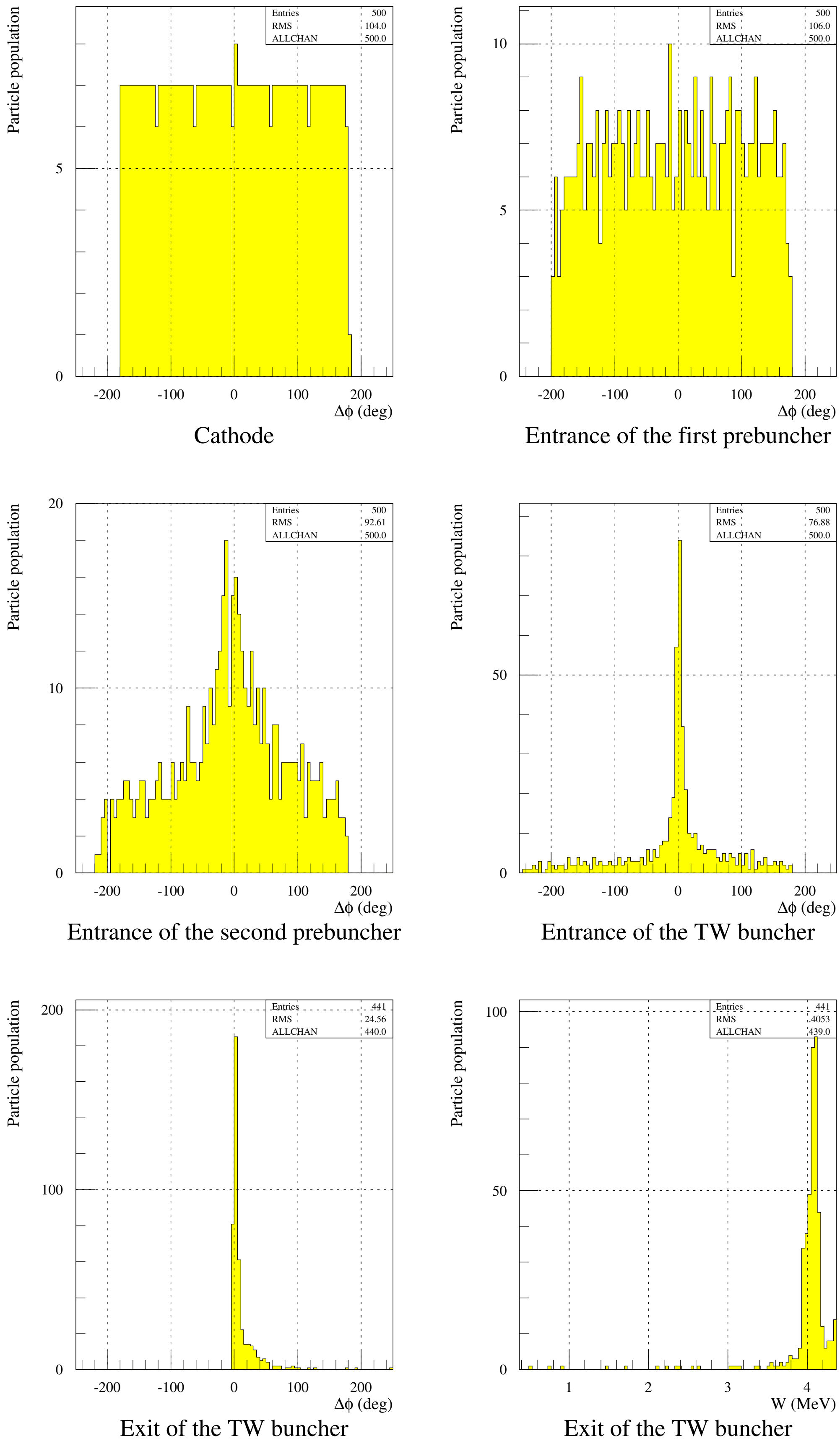


Figure 11: Two 3GHz prebuncher case with DC gun of 150 KV.

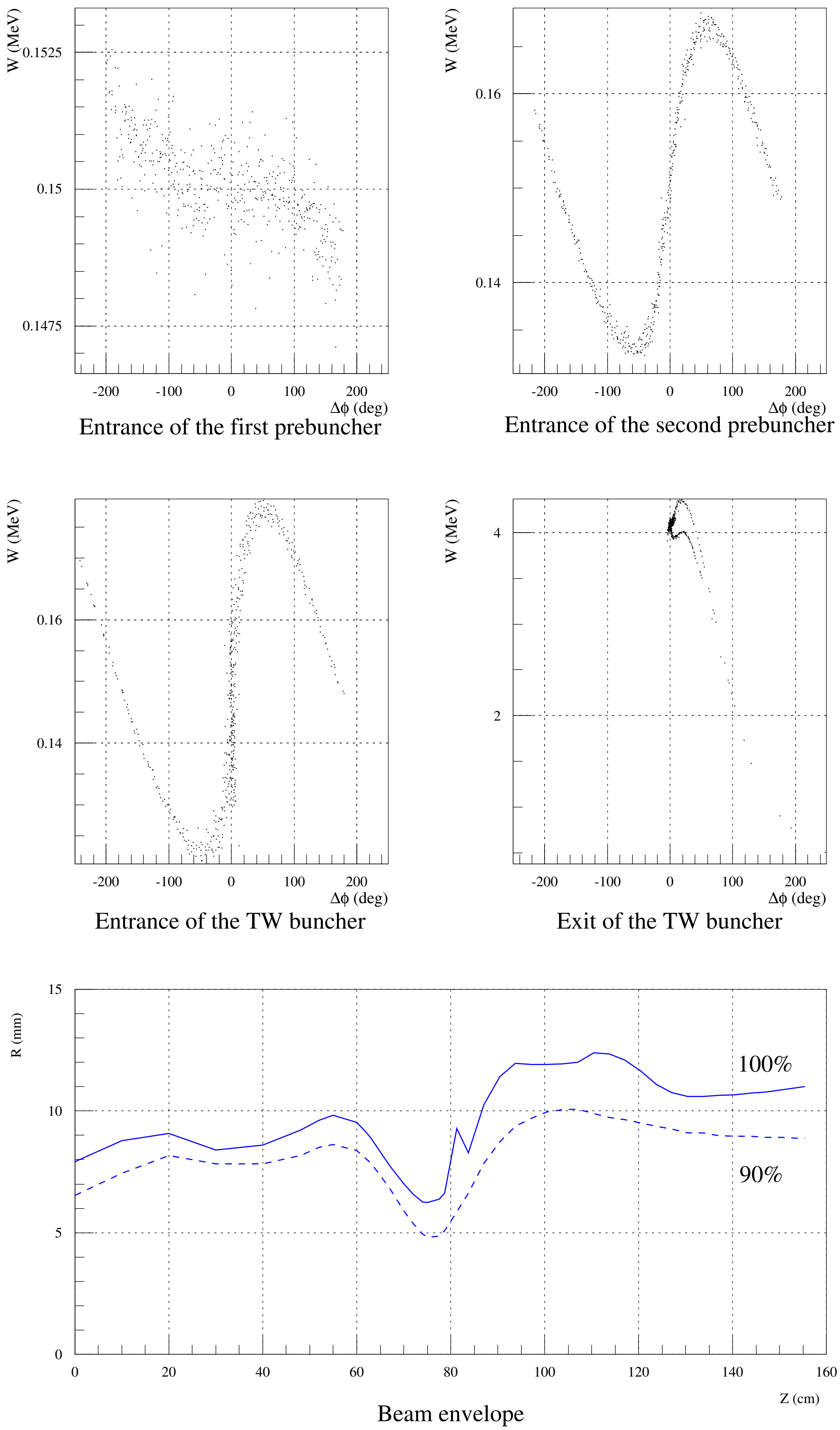


Figure 12: Two 3GHz prebuncher case with DC gun of 150 KV.

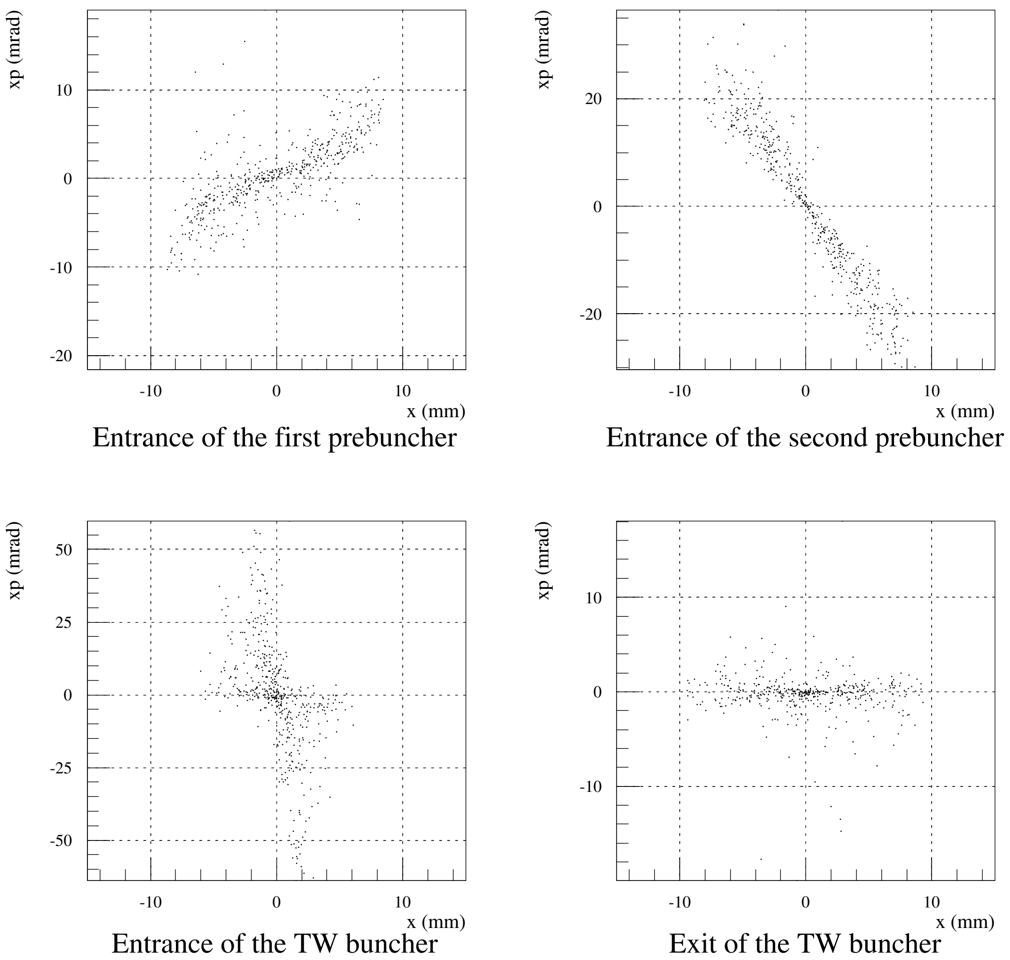
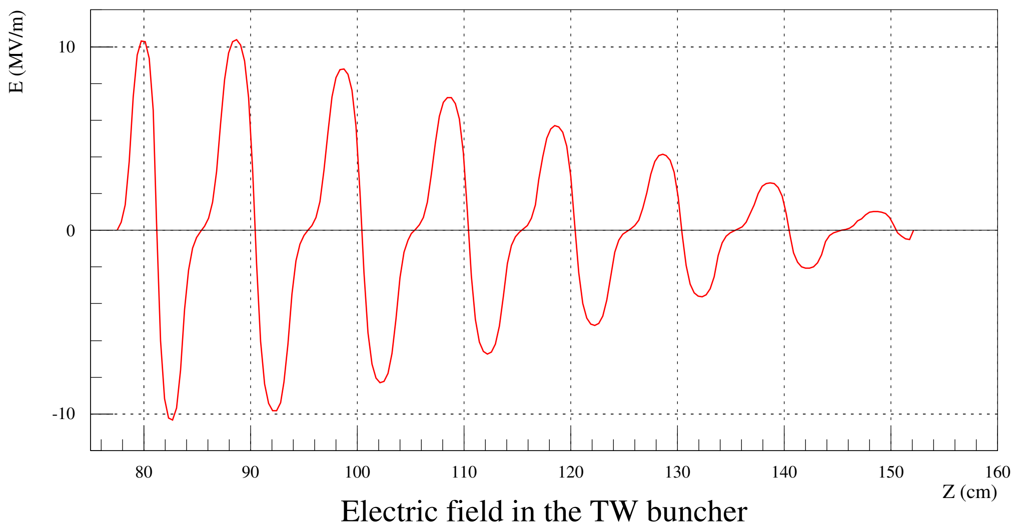
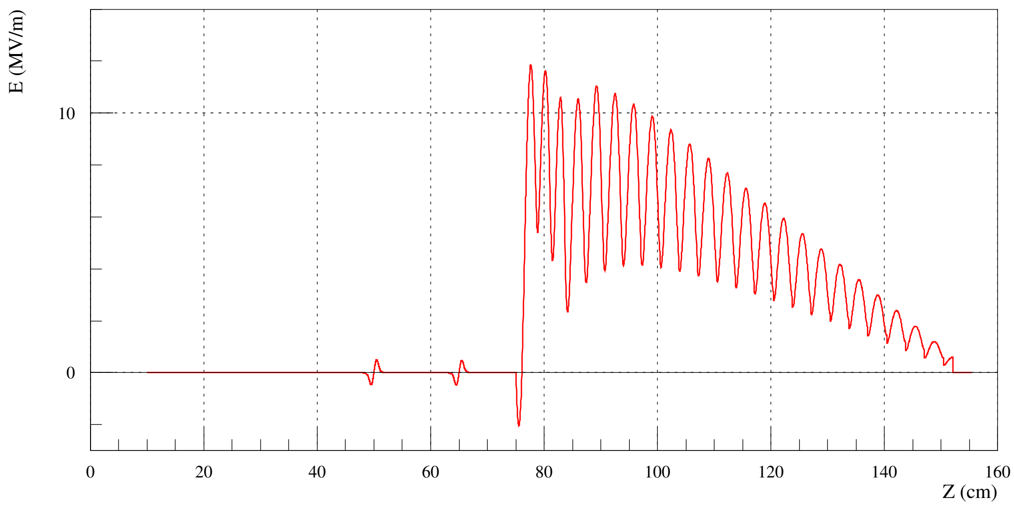


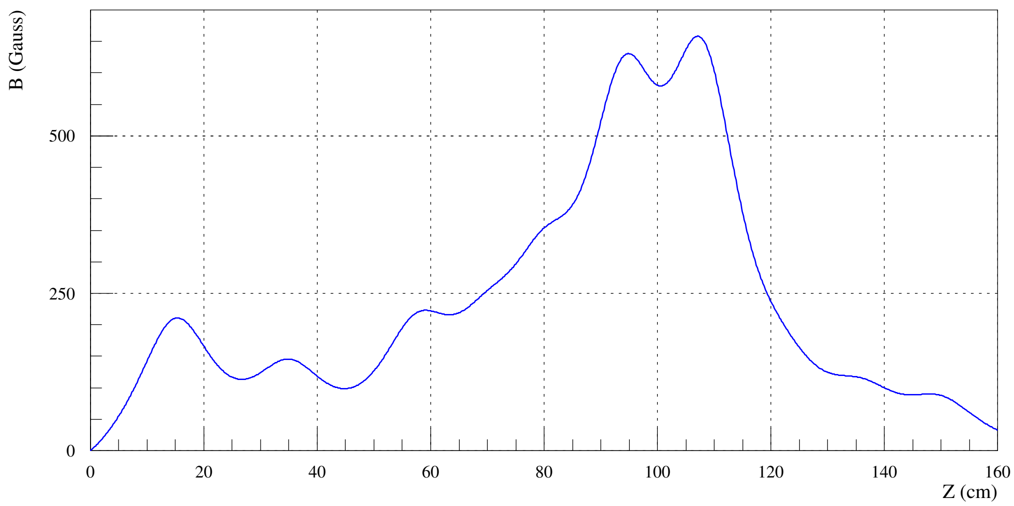
Figure 13: Two 3GHz prebuncher case with DC gun of 150 KV.



Electric field in the TW buncher



Electric field felt by the reference particle



Magnetic field

Figure 14: Two 3GHz prebuncher case with DC gun of 150 KV.

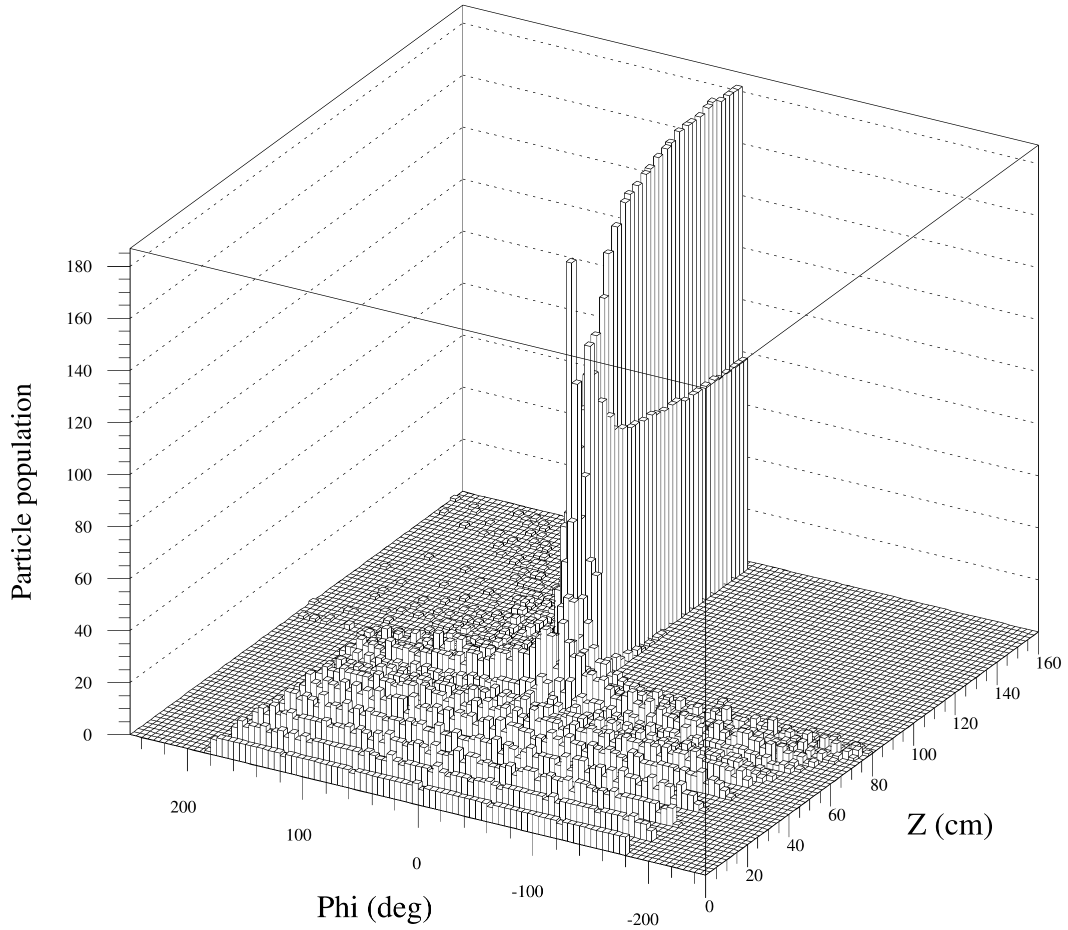
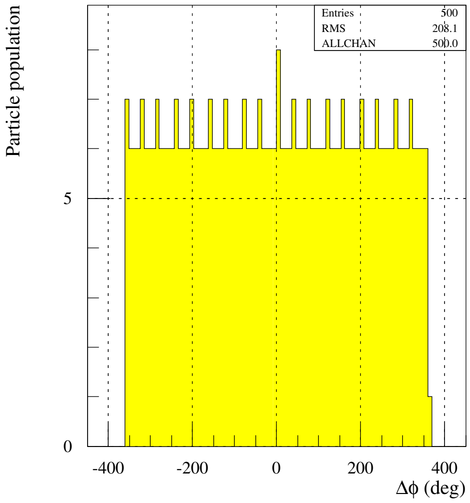
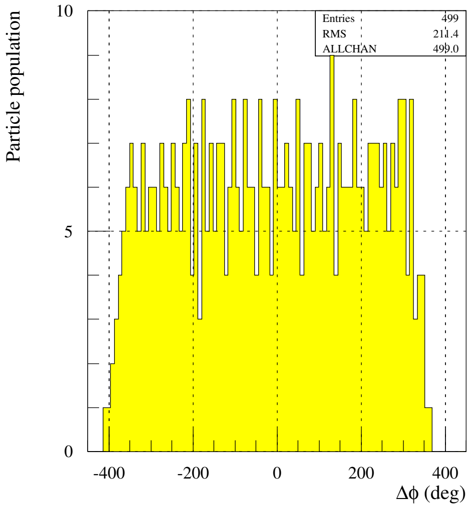


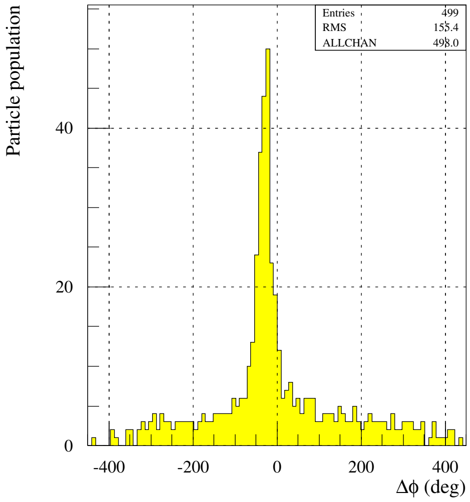
Figure 15: One 1.5GHz prebuncher case with DC gun of 90 KV.



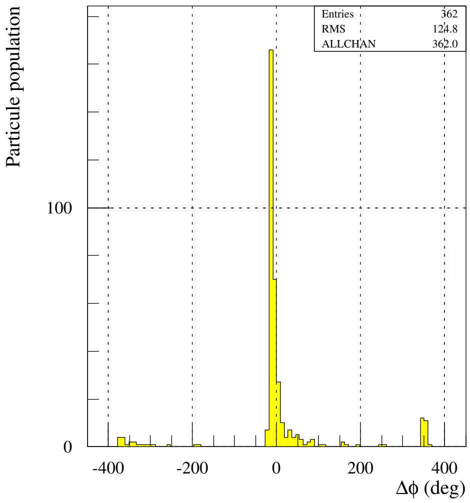
Cathode



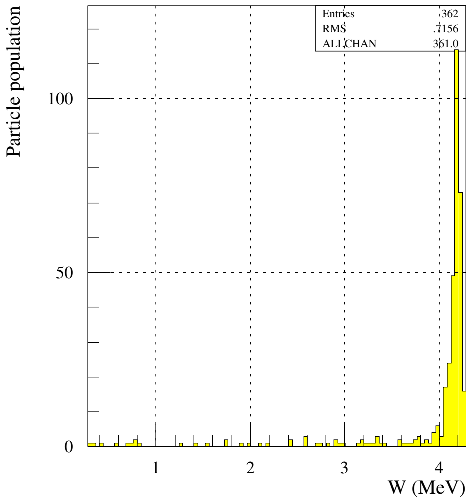
Entrance of the first prebuncher



Entrance of the TW buncher

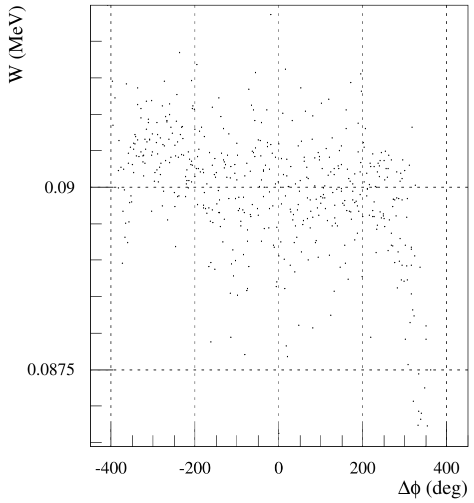


Exit of the TW buncher

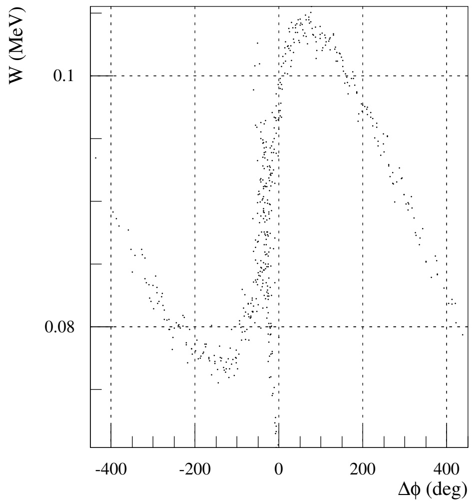


Exit of the TW buncher

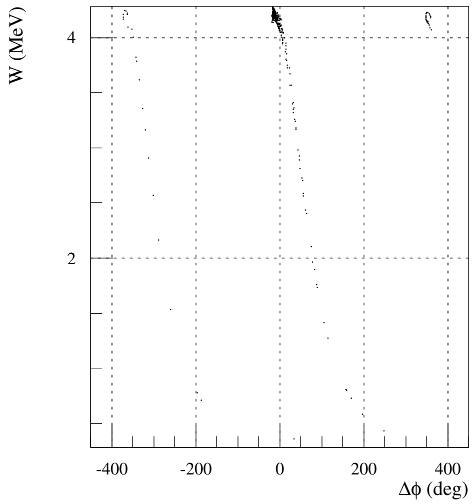
Figure 16: One 1.5GHz prebuncher case with DC gun of 90 KV.



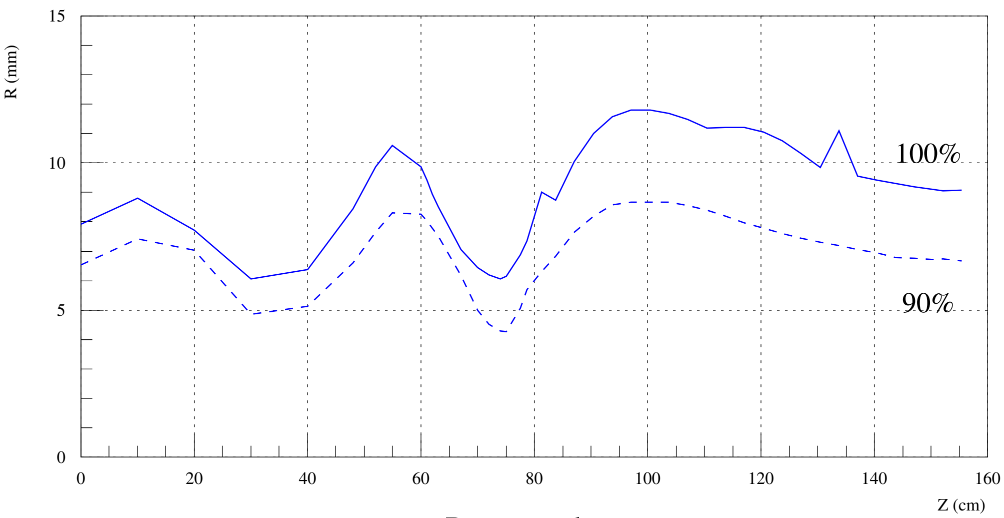
Entrance of the first prebuncher



Entrance of the TW buncher



Exit of the TW buncher



Beam envelope

Figure 17: One 1.5GHz prebuncher case with DC gun of 90 KV.

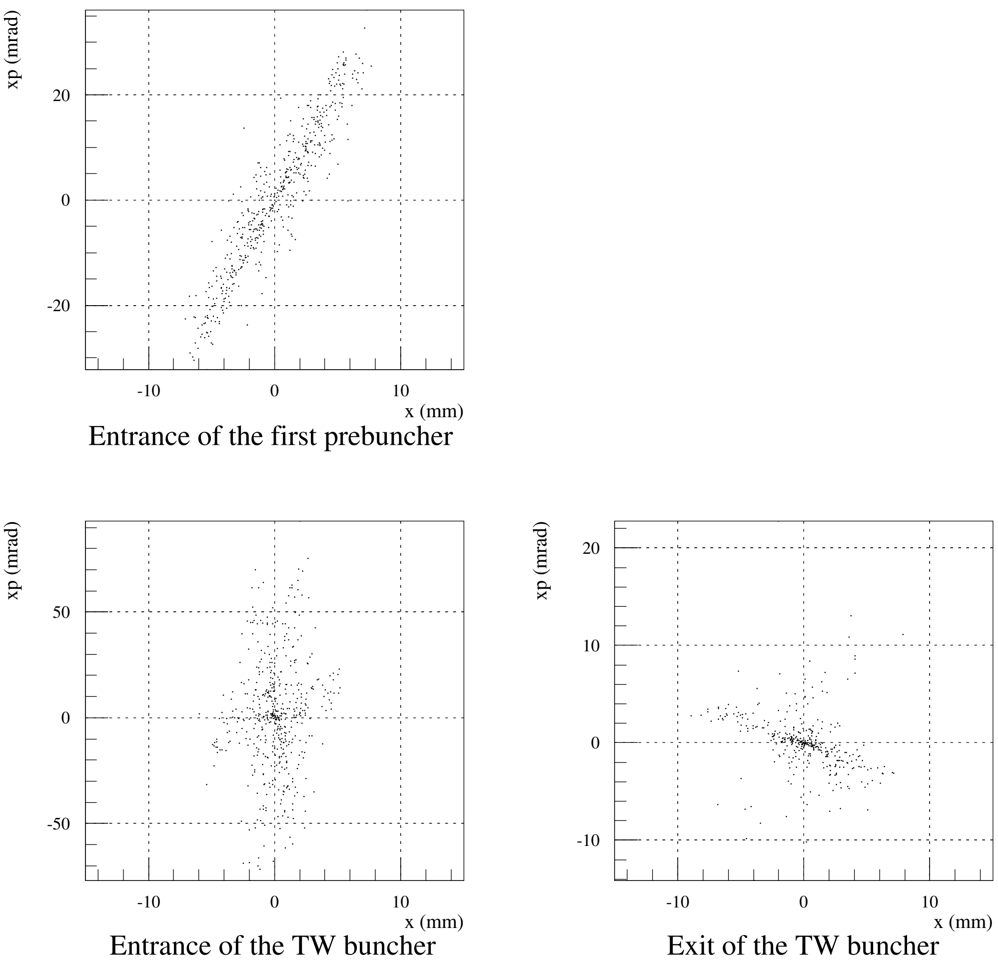
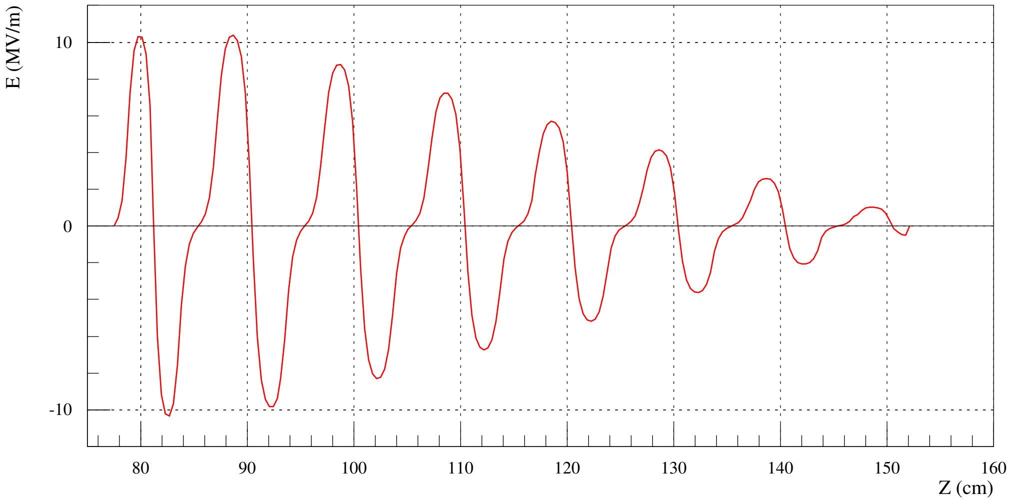
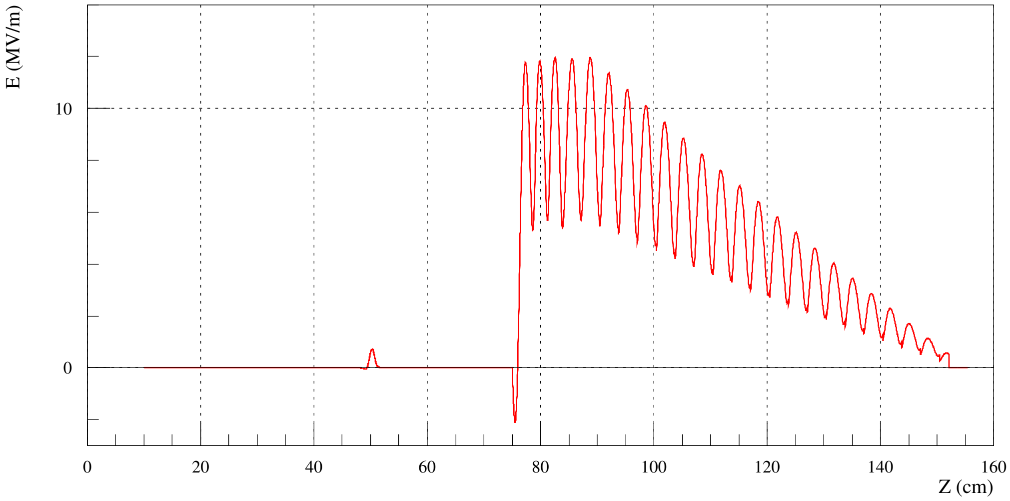


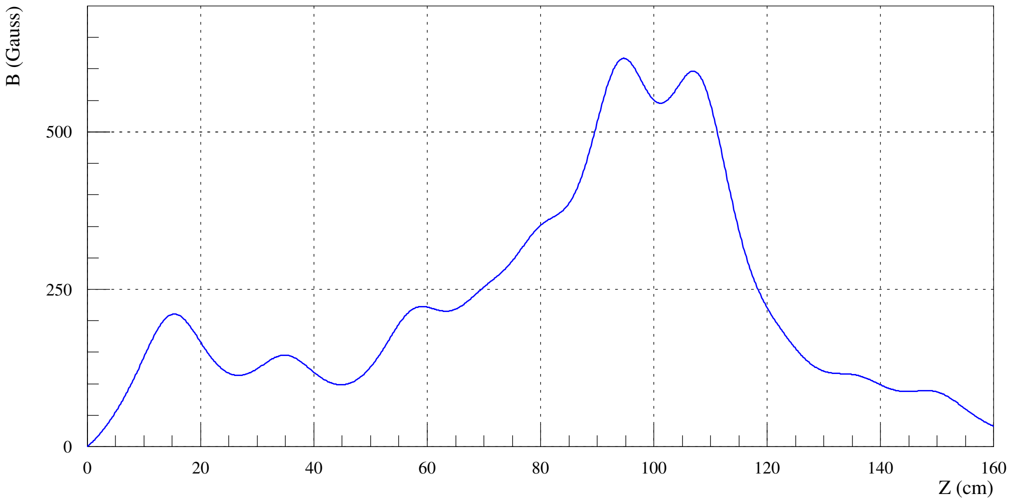
Figure 18: One 1.5GHz prebuncher case with DC gun of 90 KV.



Electric field in the TW buncher



Electric field felt by the reference particle



Magnetic field

Figure 19: One 1.5GHz prebuncher case with DC gun of 90 KV.

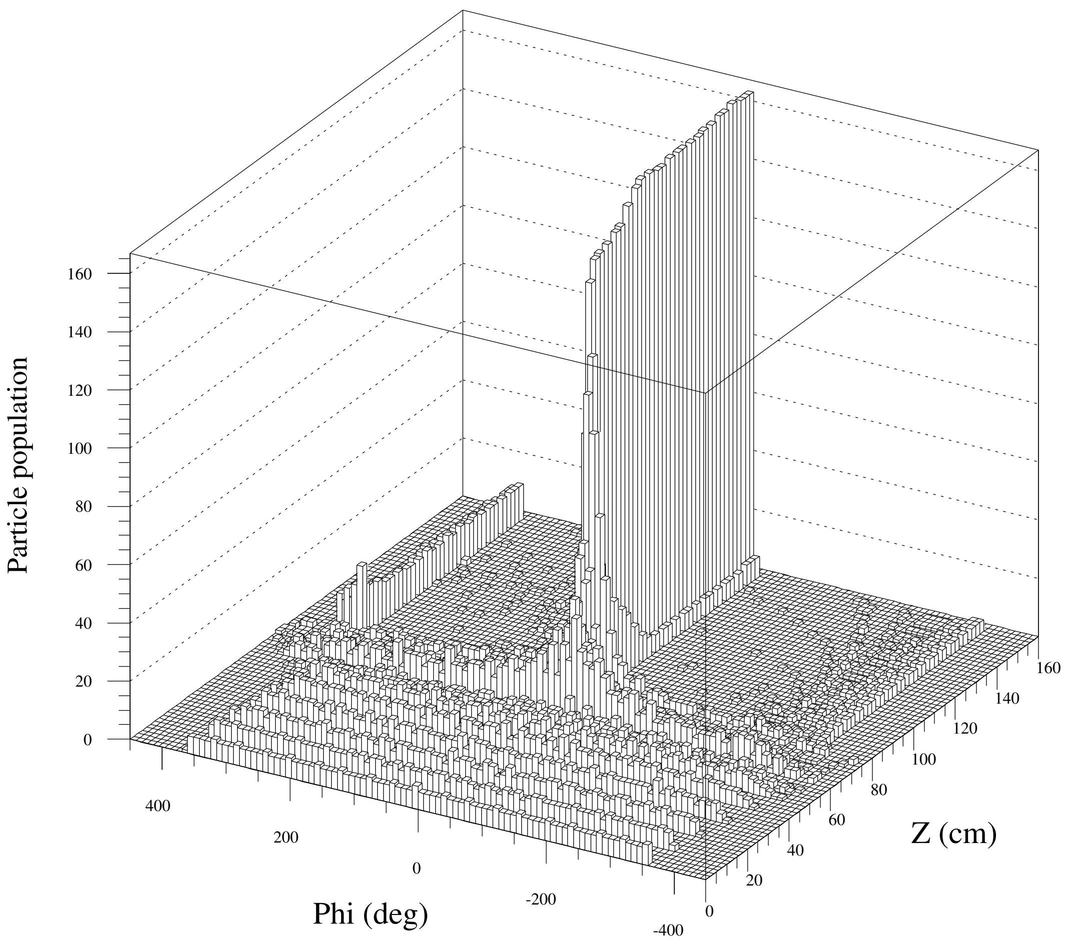


Figure 20: Two 1.5GHz prebuncher case with DC gun of 90 KV.

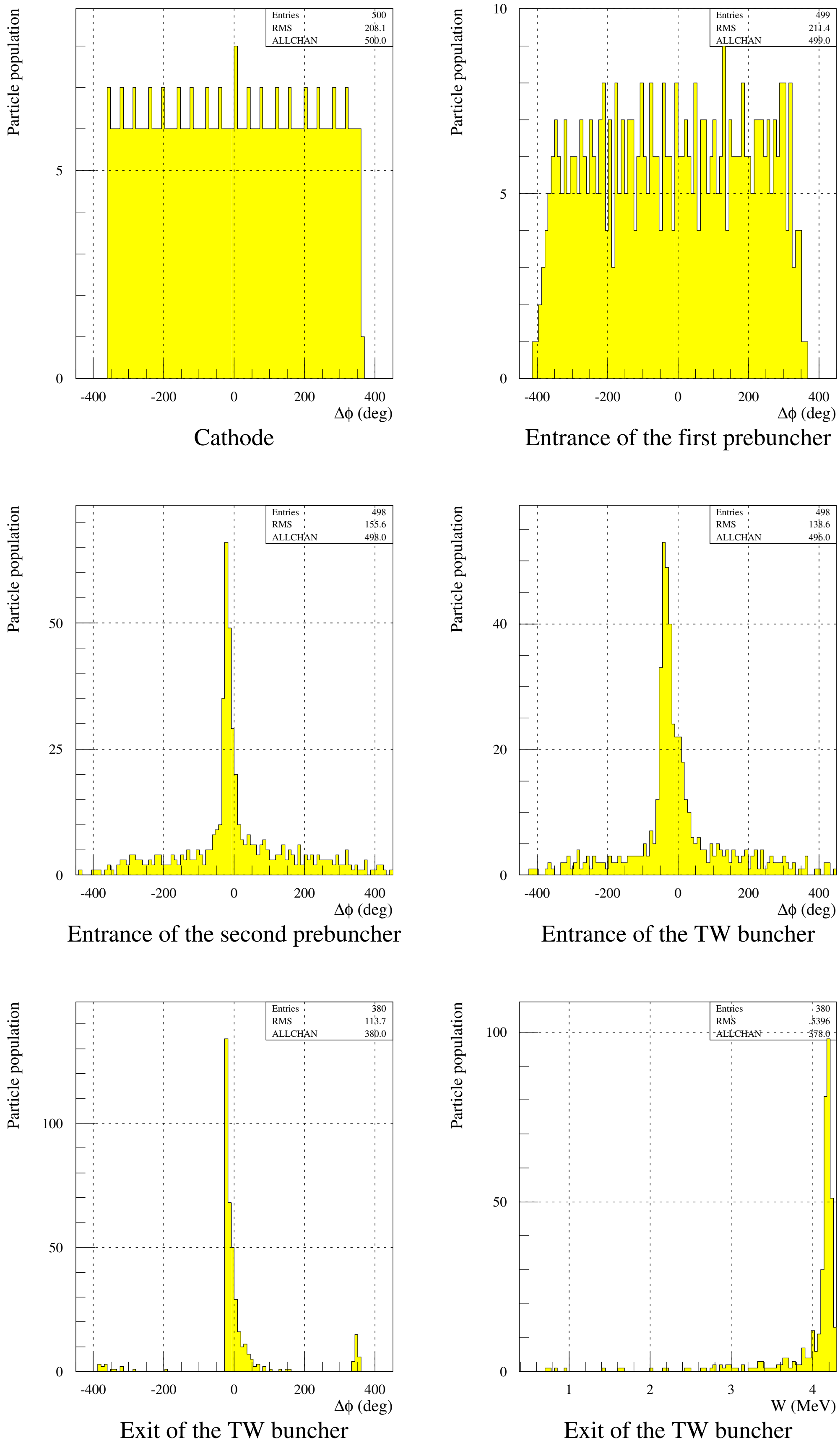


Figure 21: Two 1.5GHz prebuncher case with DC gun of 90 KV.

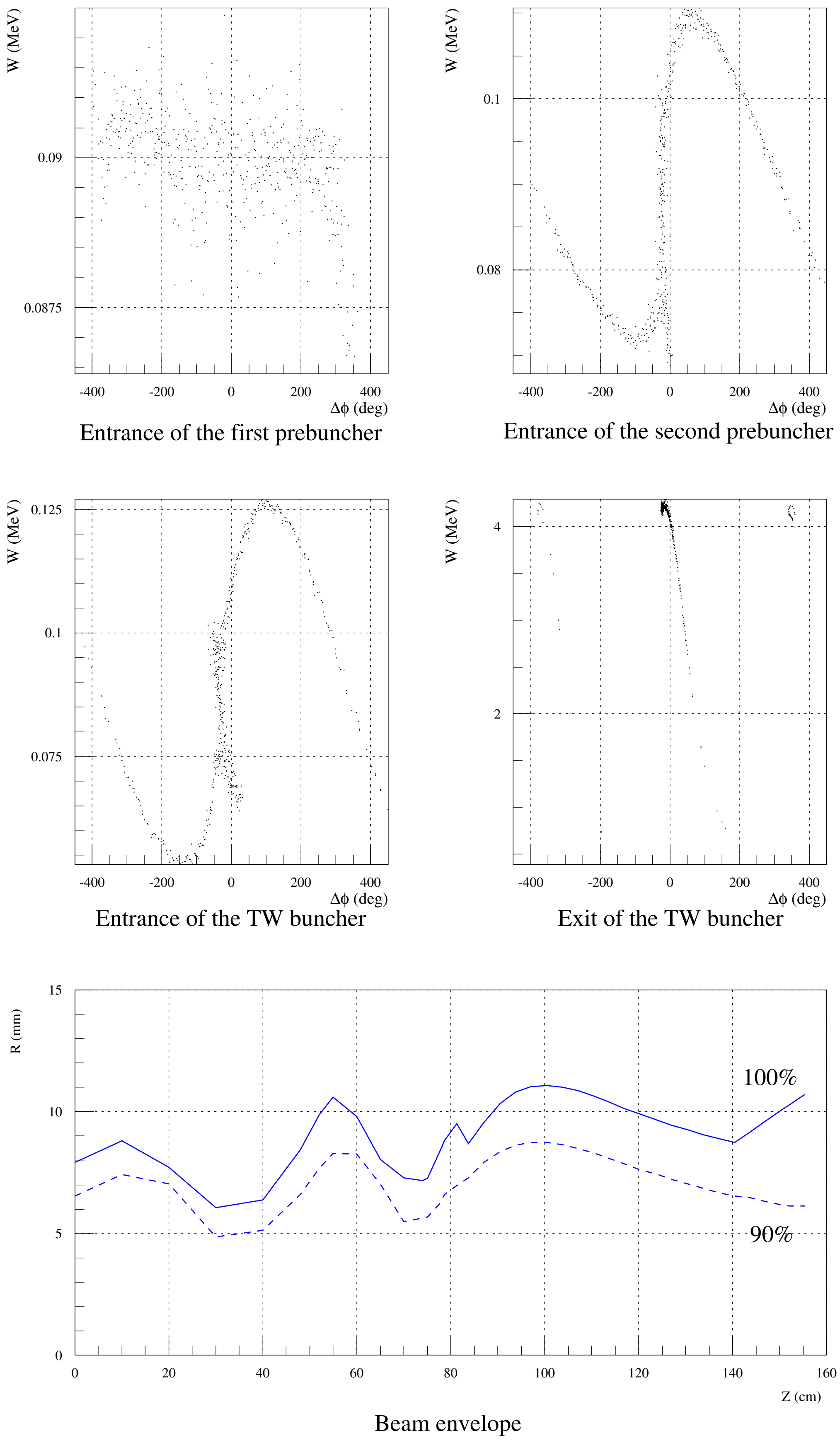


Figure 22: Two 1.5GHz prebuncher case with DC gun of 90 KV.

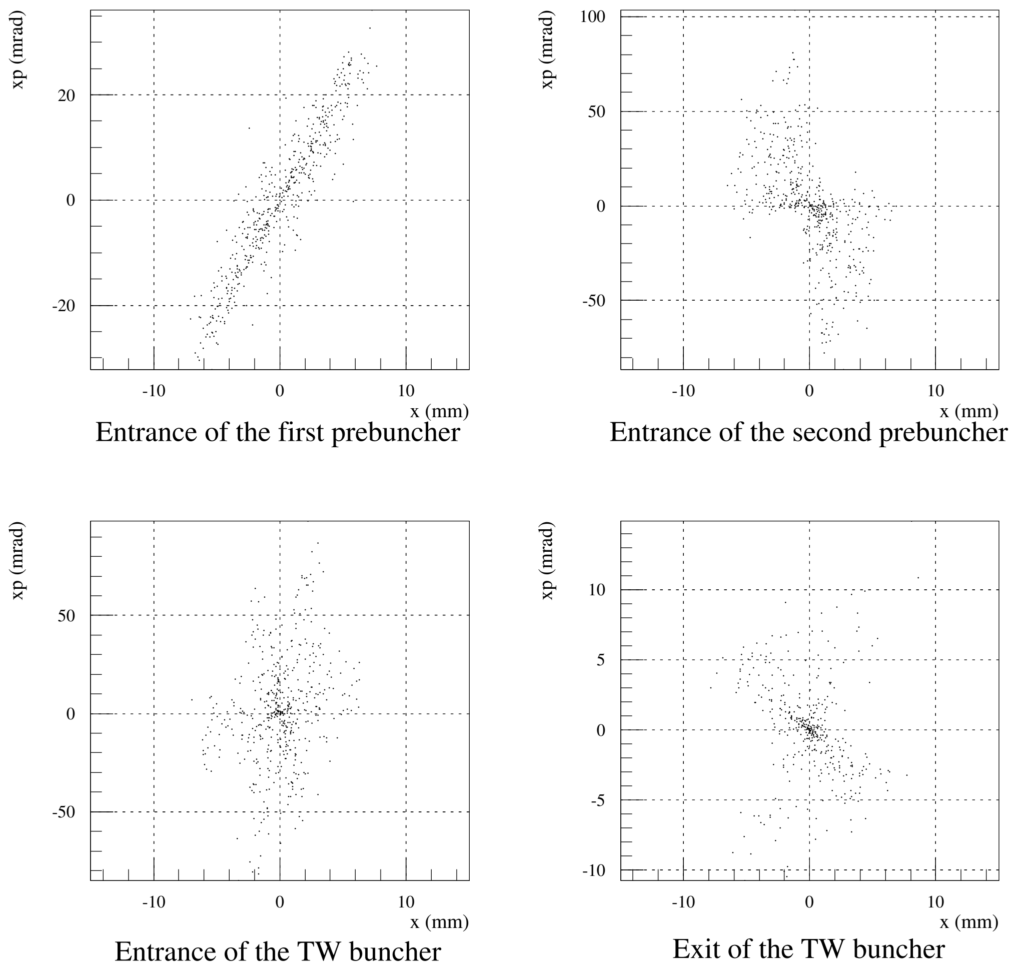
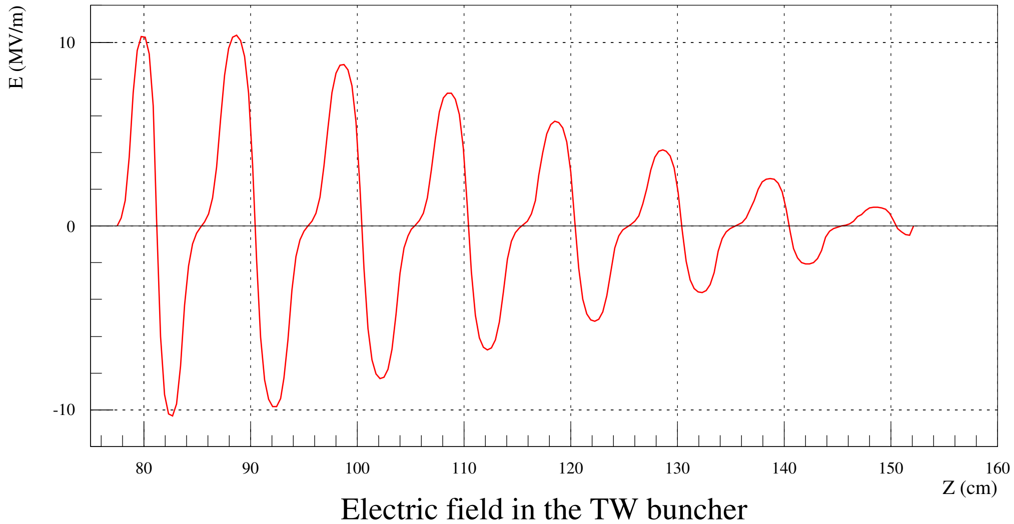
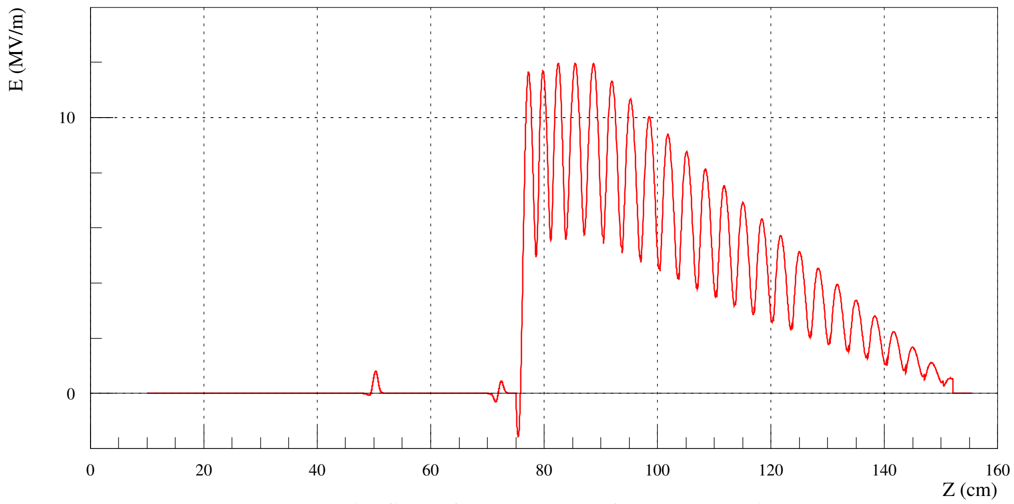


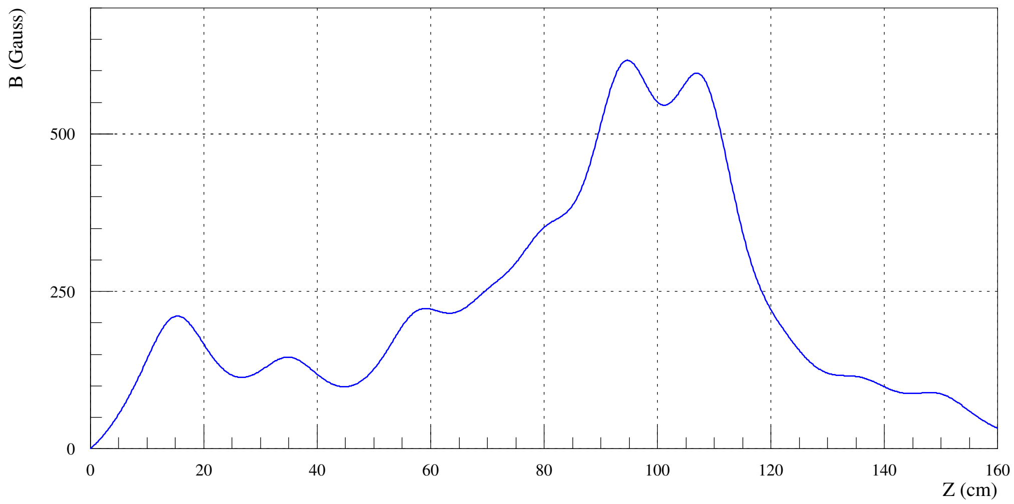
Figure 23: Two 1.5GHz prebuncher case with DC gun of 90 KV.



Electric field in the TW buncher



Electic field felt by the reference particle



Magnetic field

Figure 24: Two 1.5GHz prebuncher case with DC gun of 90 KV.

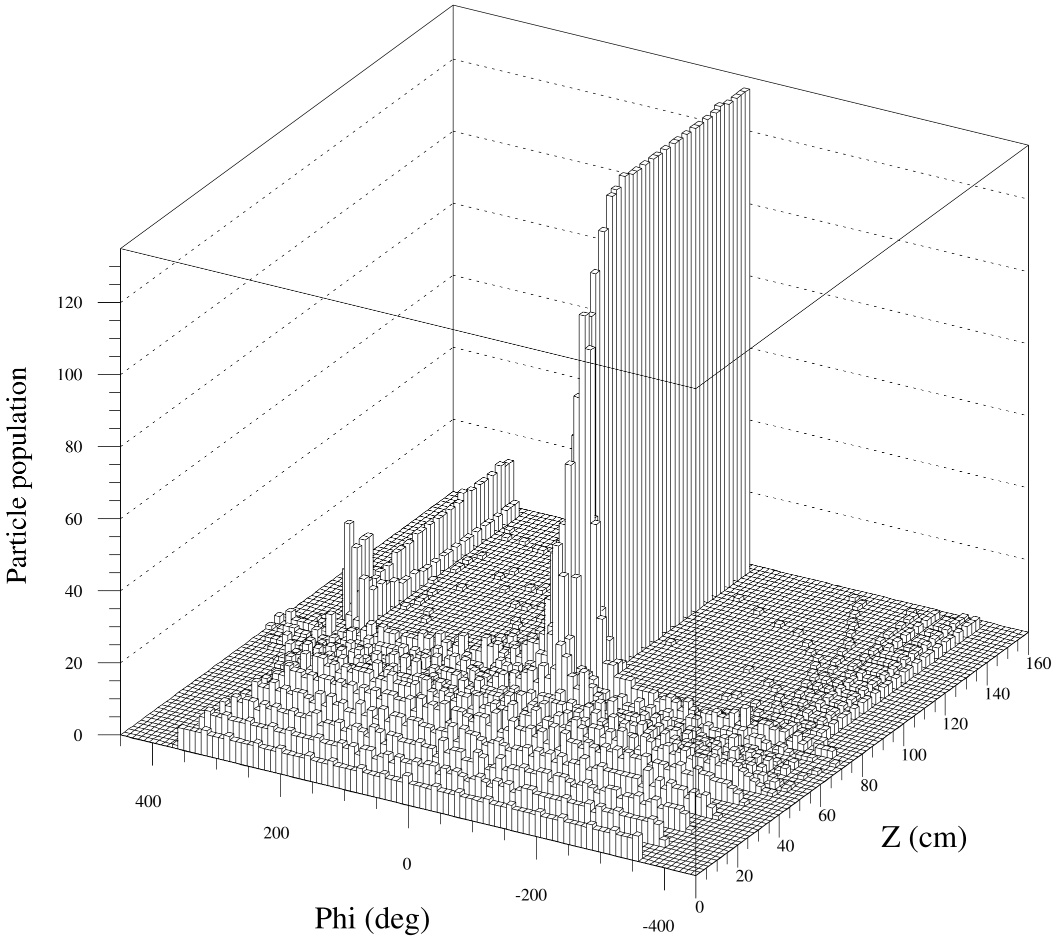
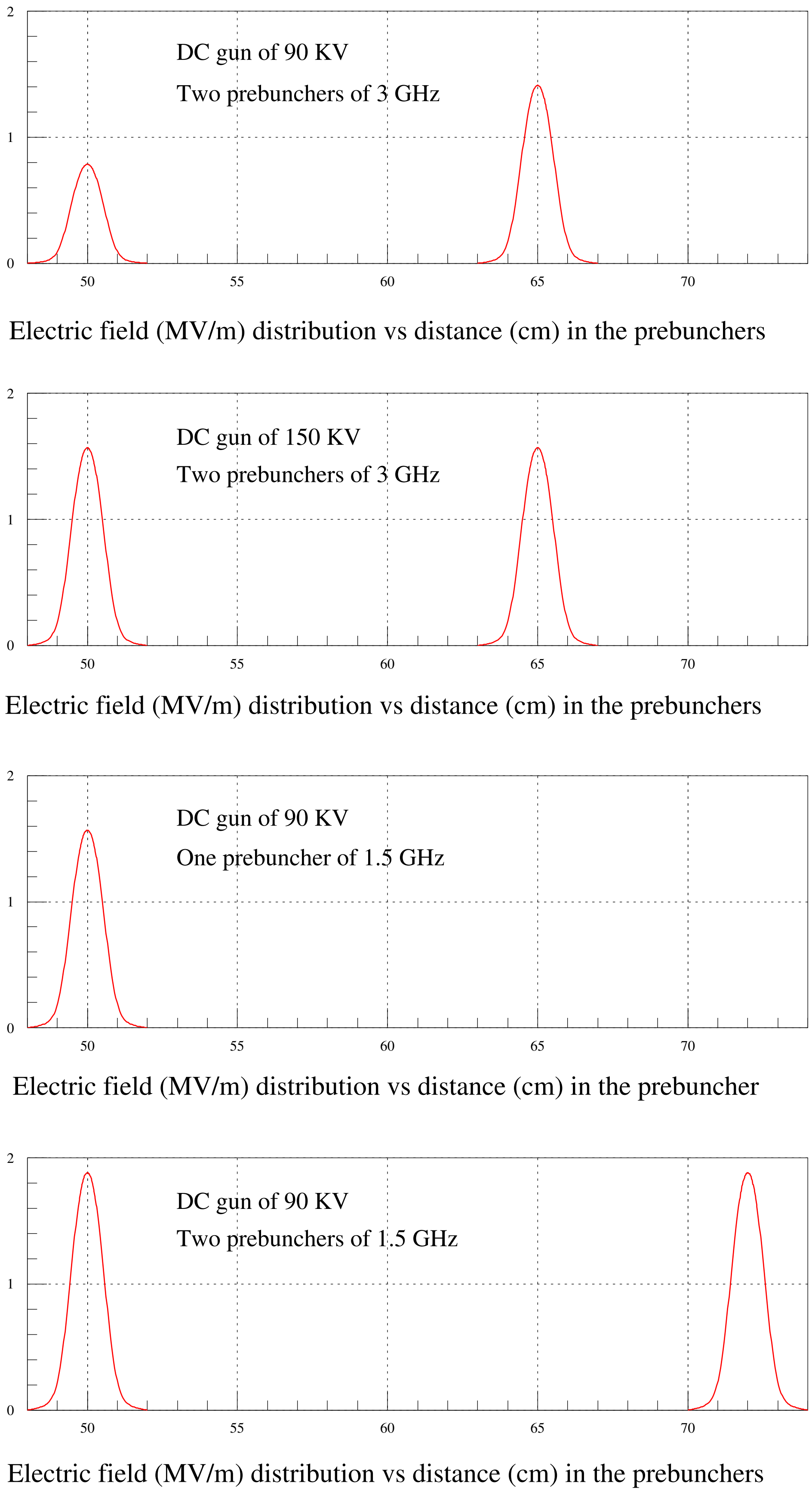


Figure 25: Prebuncher electric field distributions for the four cases.



Summary of the PARMELA simulations

In tables 2 to 5 we give a summary of the PARMELA simulations. All the statistical rms values such as ΔW, ϵ_n, and $\Delta\phi$ are measured in a range of 20 degree, and the N/N$_0$ in the tables represents the particle populations in this range. In the case where there is no subharmonic buncher(s) there are 500 particles emitted during one 3 GHz rf period. In the case where there is subharmonic buncher(s), however, there are 500 particles emitted during two 3 GHz rf periods.

E_{z0} (MV/m) TWB	W (MeV)	ΔW (MeV)	ϵ_n (mm.mrad)	$\Delta\phi$ (degree)	N/N$_0$
10	3.936	0.034	53.5	5.11	304/500
20	7.303	0.28	52.6	3.47	345/500
30	8.986	0.474	93.5	2.843	320/500

Table 2: Simulation results for the bunching system consists of two 3 GHz prebunchers and one TW buncher (DC gun voltage of 90 KV).

E_{z0} (MV/m) TWB	W (MeV)	ΔW (MeV)	ϵ_n (mm.mrad)	$\Delta\phi$ (degree)	N/N$_0$
10	3.936	0.034	53.5	5.11	304/500
20	7.303	0.28	52.6	3.47	345/500
30	8.986	0.474	93.5	2.843	320/500

Table 3: Simulation results for the bunching system consists of two 3 GHz prebunchers and one TW buncher (DC gun voltage of 150 KV).

E_{z0} (MV/m) TWB	W (MeV)	ΔW (MeV)	ϵ_n (mm.mrad)	$\Delta\phi$ (degree)	N/N$_0$	Satellite charge
10	4.208	0.033	49	5.38	208/500	21.9 %

Table 4: Simulation results for the bunching system consists of one 1.5 GHz prebuncher, one 3 GHz prebuncher and one TW buncher (DC gun voltage of 90 KV).

E_{z0} (MV/m) TWB	W (MeV)	ΔW (MeV)	ϵ_n (mm.mrad)	$\Delta\phi$ (degree)	N/N_0	Satellite charge
10	4.124	0.04	37.5	4.7	244/500	13.3 %

Table 5: Simulation results for the bunching system consists of one 1.5 GHz prebuncher and one TW buncher (DC gun voltage of 90 KV).

E_{z0} (MV/m) TWB	W (MeV)	ΔW (MeV)	ϵ_n (mm.mrad)	$\Delta\phi$ (degree)	N/N_0	Satellite charge
10	4.07	0.035	44	5.63	222/500	10.3 %

Table 6: Simulation results for the bunching system consists of two 1.5 GHz prebuncher and one TW buncher(DC gun voltage of 90 KV).

Multibunch instabilities in the buncher

One important question concerning the TW buncher design is whether HOM couplers are needed or not to prevent the multibunch transverse instabilities. To answer this question we look at an accelerating section of 0.8 m long working at $2\pi/3$ mode. The dimension of this structure is similar to that of the TW buncher proposed above. Numerical simulations show that when the bunch separation is 10 cm there is no need to install HOM couplers, however, if the bunch separation is 20 cm HOM couplers should be installed on each cell since the required loaded quality factor of the dipole mode should be lower than 80. The simulation results are given in Figs. 26, 27, and 28.

HOM couplers on TW buncher

In this section we discuss the HOM coupler design for the TW buncher structure. Since we will install HOM couplers on each cell as shown in Fig. 29 one can estimate the loaded TM_{110} mode quality factor $Q_{L,110}$ as follows:

$$Q_{L,110} = \frac{Q_{0,110}}{1+\beta_{4,110}} \tag{18}$$

where $Q_{0,110}$ is the unloaded quality factor and $\beta_{4,110}$ can be expressed as [10]:

$$\beta_{4,110}(l) = \frac{\pi Z_0 k k_{10} l^6 e^{-2\alpha_c t} J_1'(u_{11})^2}{144(ln(\frac{4l}{w})-1)^2 ABRR_{s,110}(R+h)J_2^2(u_{11})} \tag{19}$$

where h is the cavity length, R is the cavity radius, $R_{s,110}$ is the metal surface resistance at the TM_{110} mode frequency, λ_{110} is the wavelength of the TM_{110} mode, $Z_0 = 120\pi$, $k = 2\pi/\lambda_{110}$, $k_{10} = k(1-(\lambda_{110}/2A)^2)^{1/2}$, $\alpha_c = (2\pi/\lambda_{110})((\lambda_{110}/2l)^2-1)^{1/2}$, A and B are the width and the height of HOM waveguides, l and w are the width and the height of the four rectangular coupling slots with l parallel to the magnetic field, and t is the wall thickness between the cavity inner surface and the waveguide. As an example, taking $A = 0.044$ m, $B = 0.02$m, $w = 0.01$ m, $t = 0.003$ m, $h = 0.02$ m, and $R = 0.041$ m, one gets $\beta_{4,110} = 186$ for $l = 0.03$ m. Fig. 30 shows $\beta_{4,110}$ vs the slot length l.

Conclusions

- Considering the beam loading effect a preliminary design of TW buncher is given.
- Bunching systems proposed for CTF3 have been simulated by using PARMELA. For the initial stage with two prebunchers working on 3 GHz the proposed bunching system can provide bunches satisfying the design goal. For the norminal stage with only one (or two) 1.5 GHz prebuncher this bunching system works equally well except the charge population in a satellite of 13% (or 10%) exceeding the design value of 5%. To limit the charge populations in the satellite one should avoid to use 3 GHz prebuncher before TW buncher. Obviously, more works will be done to reduce the satellite charges.
- Multibunch instabilities in the TW buncher have been studied numerically. It is concluded that on the cells of the TW buncher HOM mode couplers should be installed and the loaded quality factor of the dipole mode should be lower than 80.
- An analytical design of the HOM coupler is given.

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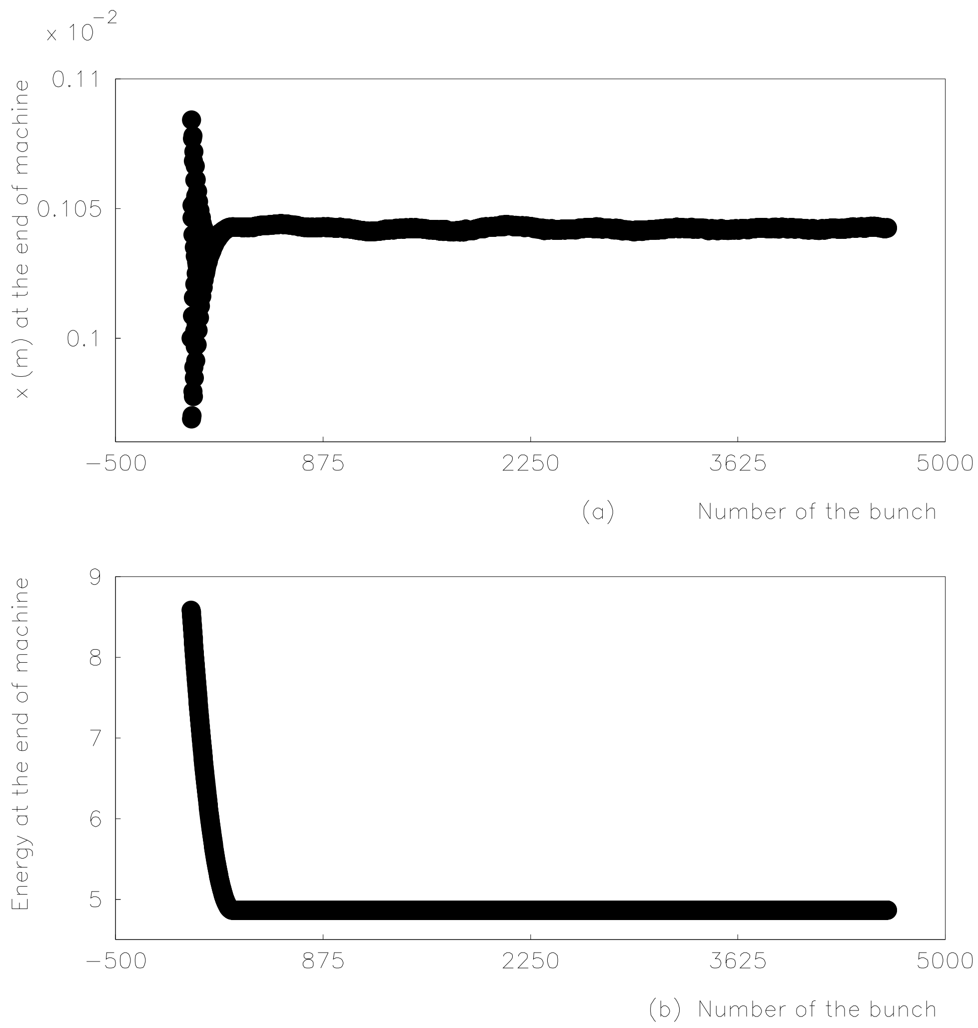


Figure 26: The bunch separation is 10 cm, and the TW buncher is not damped. (a) The transverse motion of a bunch train with an initial offset of 1 mm. (b) The energy gain of the bunch train.

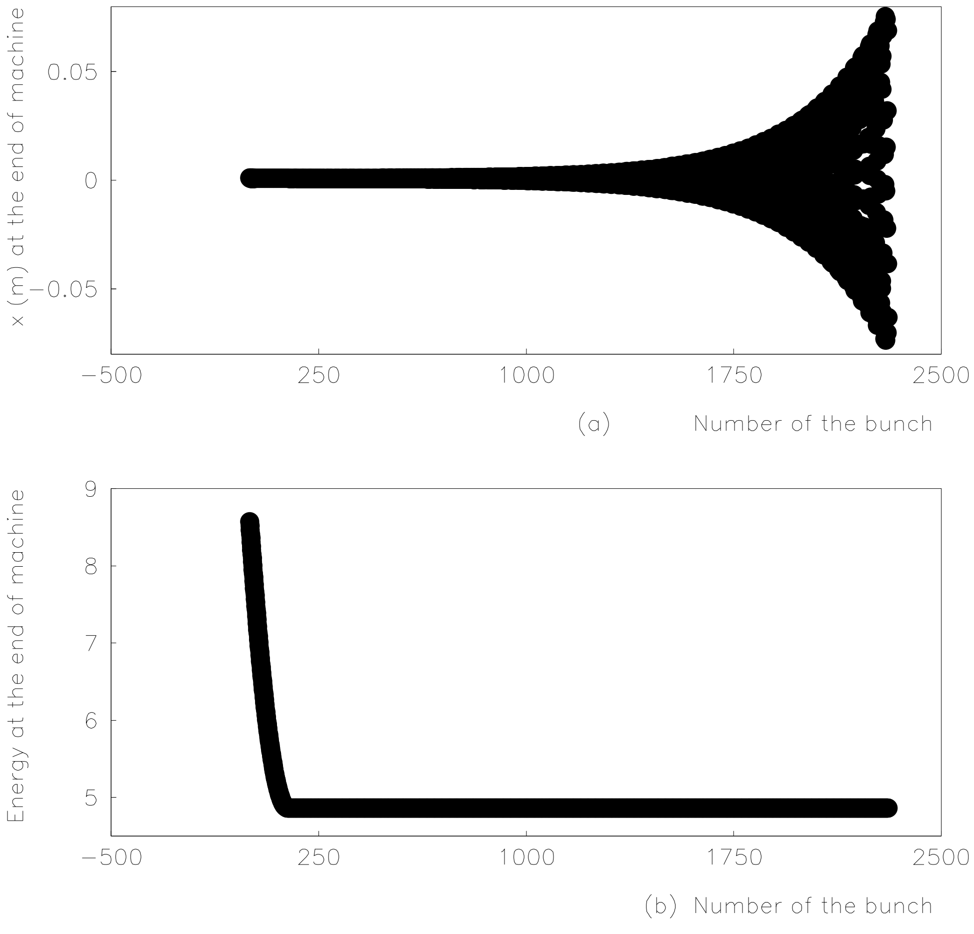
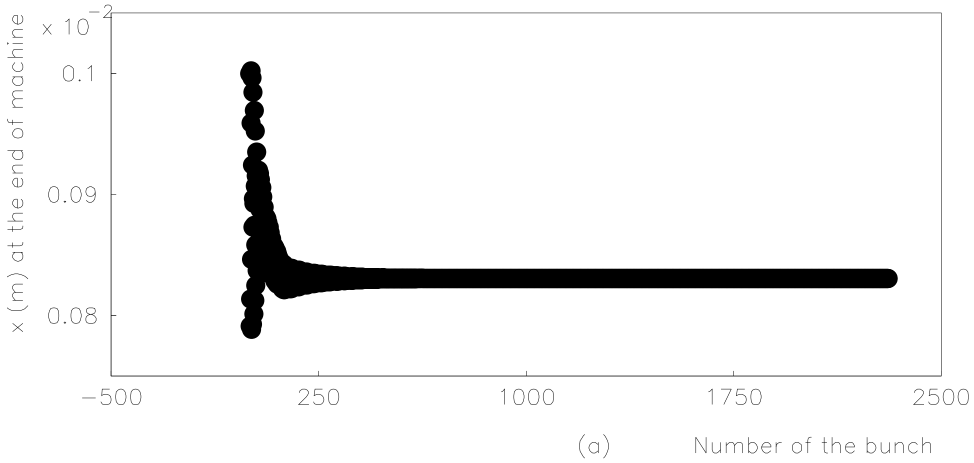


Figure 27: The bunch separation is 20 cm, and the TW buncher is damped with $Q_{L,110} = 93$. (a) The transverse motion of a bunch train with an initial offset of 1 mm. (b) The energy gain of the bunch train.



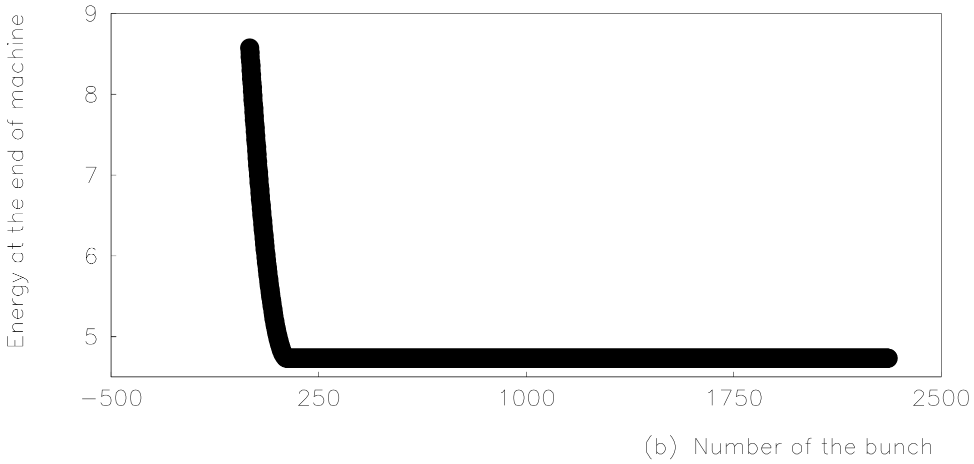


Figure 28: The bunch separation is 20 cm, and the TW buncher is damped with $Q_{L,110} = 80$. (a) The transverse motion of a bunch train with an initial offset of 1 mm. (b) The energy gain of the bunch train.

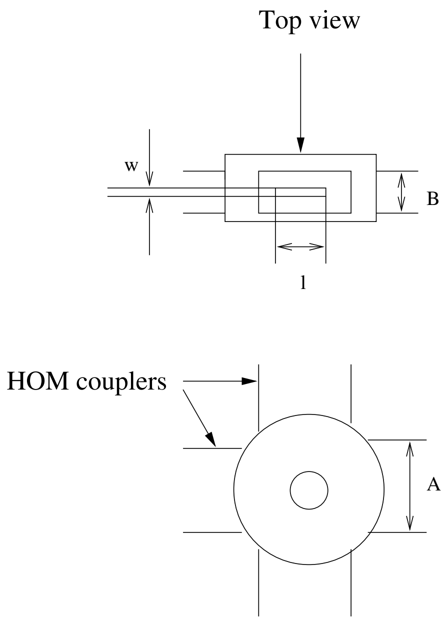


Figure 29: The schematical drawing of a cell loaded by four HOM waveguides.

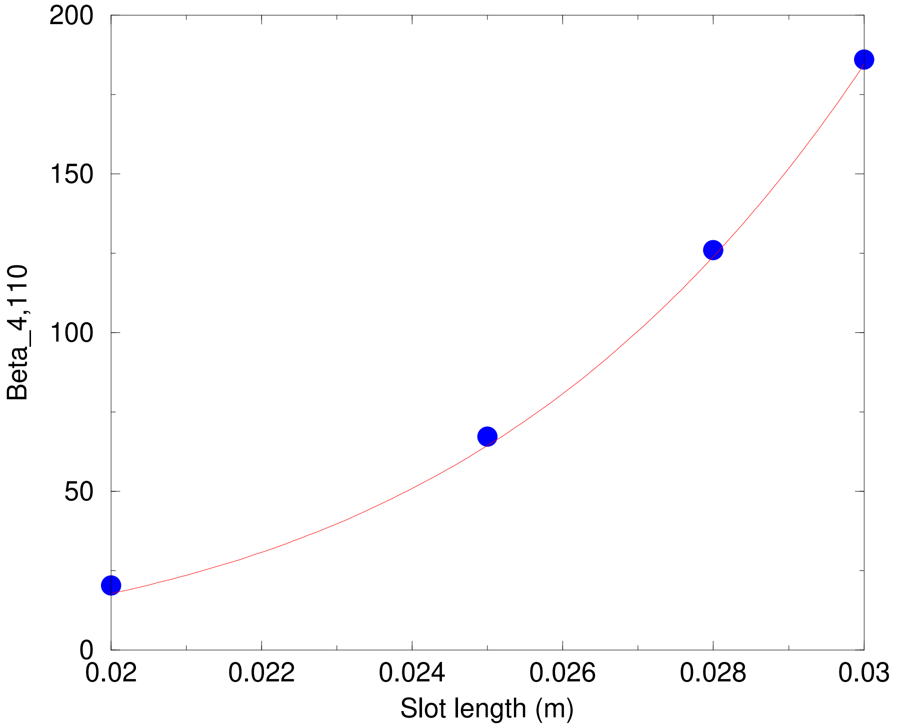


Figure 30: $\beta_{4,110}$ vs slot length l.