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First Simulations of a RF gun (Clic Test Facility) done with the self-consistent code PRIAM

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1. Introduction

In the framework of CLIC studies a 3 GHz RF gun with a laser driven photoemissive cathode is under construction in the PS division at CERN [1]; the aim of this device is to test the production of very high charge bunches with good characteristics, as required by the subsequent magnetic compression and acceleration in the CLIC driving LINAC (where a 30 GHz structure has to be excited). The dynamics in the two cavities of the RF gun has been studied by the authors with the aid of the code PRIAM[2].

PRIAM is a Particle In Cell code developed at LAL by one of us (GLM) on the basis of the finite elements library MODULEF; it provides a self-consistent calculation of the dynamics, including space charge and wake fields; the RF fields (calculated by the code MODEHF of the same library) and a possible external magnetic field are superimposed. The advantage of the finite elements approach is a very flexible triangular mesh, that provides an easy and precise description of the boundary lines and an accurate computation of the fields in the beam region.

In this note we present the first simulations on the geometry of the CTF RF gun (Fig 1): the calculation of frequency and field map of the π mode, used for particle acceleration; the results of the dynamics for a bunch of 1 nC charge and 8 psec length; this case, although very far away from CLIC requirements (= 150 nC), is well referenced having been studied for BNL gun[3].

2. Eigenmodes and corresponding B and E maps.

With the geometry and the mesh shown in Fig. 1 the following eigen-frequencies have been calculated:

$$F_0 = 3029.155\,MHz \qquad F_\pi = 3031.142\,MHz$$

where the subscripts indicate the modes 0 and π. The ratio between the maxima of E on the axis of the two cells is:

$$\frac{E_1}{E_2} = 1.14$$

After tuning the second cell (by decreasing its diameter by 6.88 microns), the new frequencies are:

$$F_0 = 3029.26\,MHz \qquad F_\pi = 3031.325\,MHz$$

and the ratio of maximum fields is almost 1: $E_1/E_2 = .9946$. In Fig. 2 a, are represented the frequencies of the mode 0 and π as a function the radius R of the second cavity. In the same graph is also shown the ratio E_1/E_2. At R = 39.25 mm (nominal value) we find the two rates:

$$\frac{dF_\pi}{dR} = -52MHz/mm \quad and \quad \frac{d}{dR}\frac{E_1}{E_2} = 47.6mm^{-1}$$

In Fig. 2.b are plotted the same functions, but on a larger interval of variation for R; the dependence on R is non linear.

Consulting the map of the modulus of E over all the radial plane, we have found within 1% the same value for E_1,E_2 and E_{iris} (maximum value of the modulus of E on the surface of the iris between the first and the second cell).

We have then done a last exercise with MODEHF; we have verified the following property: If two cells have identical eigen-frequencies ($F_1 = F_2$), when they are coupled the average energy accumulated in each cell should be the same; then if there is a ratio 1/2 between the volumes, it will hold the relation:

$$\frac{E_1}{E_2} = \sqrt{2}$$

The proposition has been verified the inverse way: we have chosen for the second cell a radius R such that $E_1/E_2 = 1.433 \approx \sqrt{2}$. This is achieved with cavity radii: R_1 = 39.25 mm and R_2 = 39.26 mm (for these values, the frequency of the mode π is $F_\pi = 3030.909$). We have then verified that $F_1 = F_2$: the eigen frequency of the single cell can be calculated by a strong detuning of the other one. The following values have been obtained:

$$F_1 = 3029.945\,MHz \quad and \quad F_2 = 3029.921\,MHz$$

All the results presented are in good agreement with the measurements done on the first prototype of CTF gun[4]; for example the measured frequency of the π mode is:

$$F_\pi = 3031.6$$

in air, what gives 3032.6 normalized to vacuum. Compared to the calculated value the deviation is of 4×10^{-4}.

3. 'A BNL bunch in CERN cavity'

In the first runs we have simulated the nominal bunch of ATF (BNL) : 1 nC of charge and 8 psec of length (2σ of a gaussian distribution). In figure 3 we show the relevant dynamical parameters at the exit of the structure as a function of the RF phase of the laser shot ϕ_0. The minimum of the emittance is at $\phi_0 = 50\,deg$ instead of 67 deg, as from BNL simulations; the difference is due to the increased frequency (smaller cavity radius) in a structure of the same length. In Table I we show the comparison with Mc Donald's results (achieved using PARMELA) and TBCI−SF results [5]. A bunch of 720 macroparticles has been used.

Table I

	PARMELA	TBCI – SF	PRIAM	
F_π	2895	2972	3031	MHz
$F_\pi - F_0$	1.9	1.6	2.06	MHz
E_{max}	100	100	100	MV/m
$E_{max}/E_{cathode}$	1.06	1.34	1	
E_1/E_2	1	1	1	
phase of laser shot ϕ_0	67	67	50	deg
bunch charge	1	1	1	nC
radius of the cathode	6 (= 2σ)	6	6	mm
bunch length	8.(= 4σ)	8.	8.	psec
average momentum p_{final}	4.7	4.37	4.61	MeV/c
energy dispersion $\frac{\Delta p}{p}$	1.45(= 4σ)	4.92	1.57	%
spot size (final) r	8.4(= 2σ)	10.0	10.2	mm
bunch length	2.4(= 4σ)	3.2(= 4σ)	2.47	psec
divergence dr/dz	56	62	65	mrad
emittance ε_x	25.6	49.8	65.7	mm mrad

4. Acknowledgments

We are grateful to R.Bossart who proposed some of the calculations done with MODEHF.

5. References.

1. Y. Baconnier et al. "A Clic injector test facility" CLIC note 65

2. G. Le Meur ' A mixed finite element method for particle simulation in lasertron' LAL – RT 87 – 01

3. K.T. McDonald 'Design of the Laser Driven RF electron Gun for the BNL Accelerator Test Facility' DOE/ER/3072 – 43

4. R. Bossart private communications

5. H. Kugler, W. Remmer, J. Stroede "Beam dynamics of intense particle sources simulated with the help of TBCI – SF. PS/LP Note 89 – 31

Appendix A

Emittance RMS of a beam with cylindrical symmetry.

The emittance RMS in the phase plane x x′ is defined as:

$$E_x = 4\sqrt{\overline{x^2}\,\overline{x'^2} - \overline{xx'}^2} \tag{1}$$

where the bar indicates the average done over the beam distribution, and ′ the differentiation respect to the longitudinal coordinate; the normalizing factor 4 is such that for a uniform distribution over an ellipsis in phase plane $E_x\pi$ is the area of the ellipsis. To take into account the emittance shrinking due to an adiabatic acceleration the normalized emittance $\varepsilon_x = \beta\gamma E_x$ is then introduced.

If we have a beam with axial symmetry, it is convenient to work in cylindrical coordinates:

$$\begin{aligned} x &= r\cos\theta & y &= r\sin\theta \\ x' &= r'\cos\theta - r\,\theta'\sin\theta & y' &= r'\sin\theta + r\theta'\cos\theta \end{aligned} \tag{2}$$

The beam distribution doesn't depend on θ, so that expression (1) can be recalculated using the integrals:

$$\frac{1}{2\pi}\int_0^{2\pi}\sin^2 x\,dx = \frac{1}{2\pi}\int_0^{2\pi}\cos^2 x\,dx = \frac{1}{2} \qquad \frac{1}{2\pi}\int_0^{2\pi}\sin x\cos x\,dx = 0$$

getting the result:

$$\varepsilon_x = 2\beta\gamma\sqrt{\overline{r^2}\,\overline{r'^2} - \overline{rr'}^2 + \overline{r^2}\,\overline{r^2\theta'^2}} \tag{3}$$

The term $\overline{r^2\theta'^2}$ is the average of the square transverse velocity: if the cavity is excited in an axial symmetrical TM mode there are not transverse forces due to RF; then if we neglect the transverse thermal velocities at the cathode and consider a case without a superimposed solenoid focusing, the following relation holds:

$$\varepsilon_x = 2\beta\gamma\sqrt{\overline{r^2}\,\overline{r'^2} - \overline{rr'}^2} \tag{4}$$

This is the emittance calculated by PRIAM. In PS/LP note 89−31 instead has been used the geometrical emittance:

$$\varepsilon_{TBCI} = \sqrt{\overline{r^2}\,\overline{r'^2} - \overline{rr'}^2} = \frac{\varepsilon_x}{2\beta\gamma} \tag{5}$$

and in Mc Donald's simulations of BNL gun is used $\varepsilon_{BNL} = \frac{\varepsilon_x}{4}$.

Figure 1: Gun geometry and integration mesh.

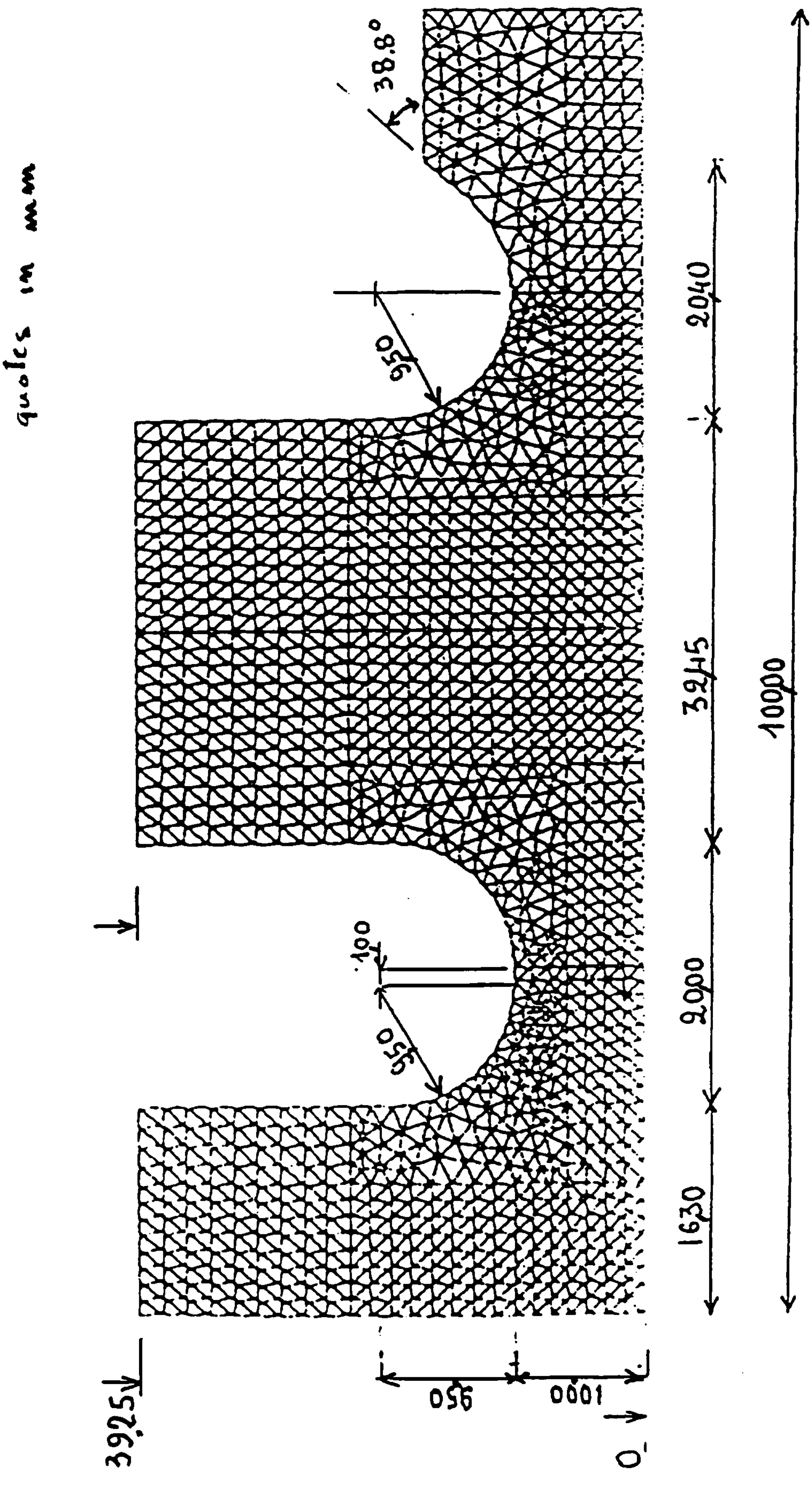

Figure 2: Frequencies of the modes 0 and π, and ratio between the maximum E field on the axis of the two cavities as a function of the radius R of the second cavity.

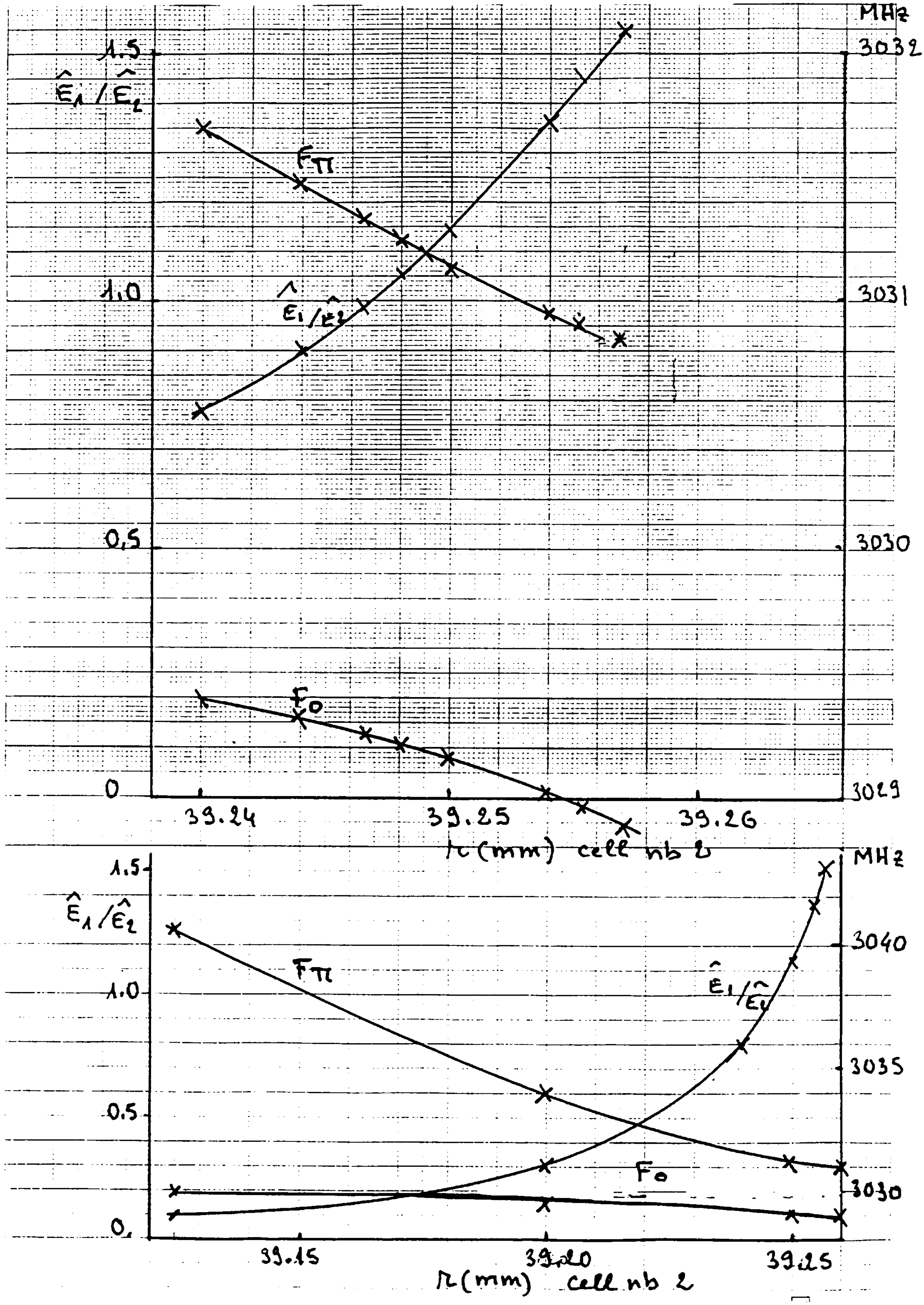

Figure 3: Relevant dynamical parameters at the end of the RF gun as a function of the phase of the laser shot ϕ_0.

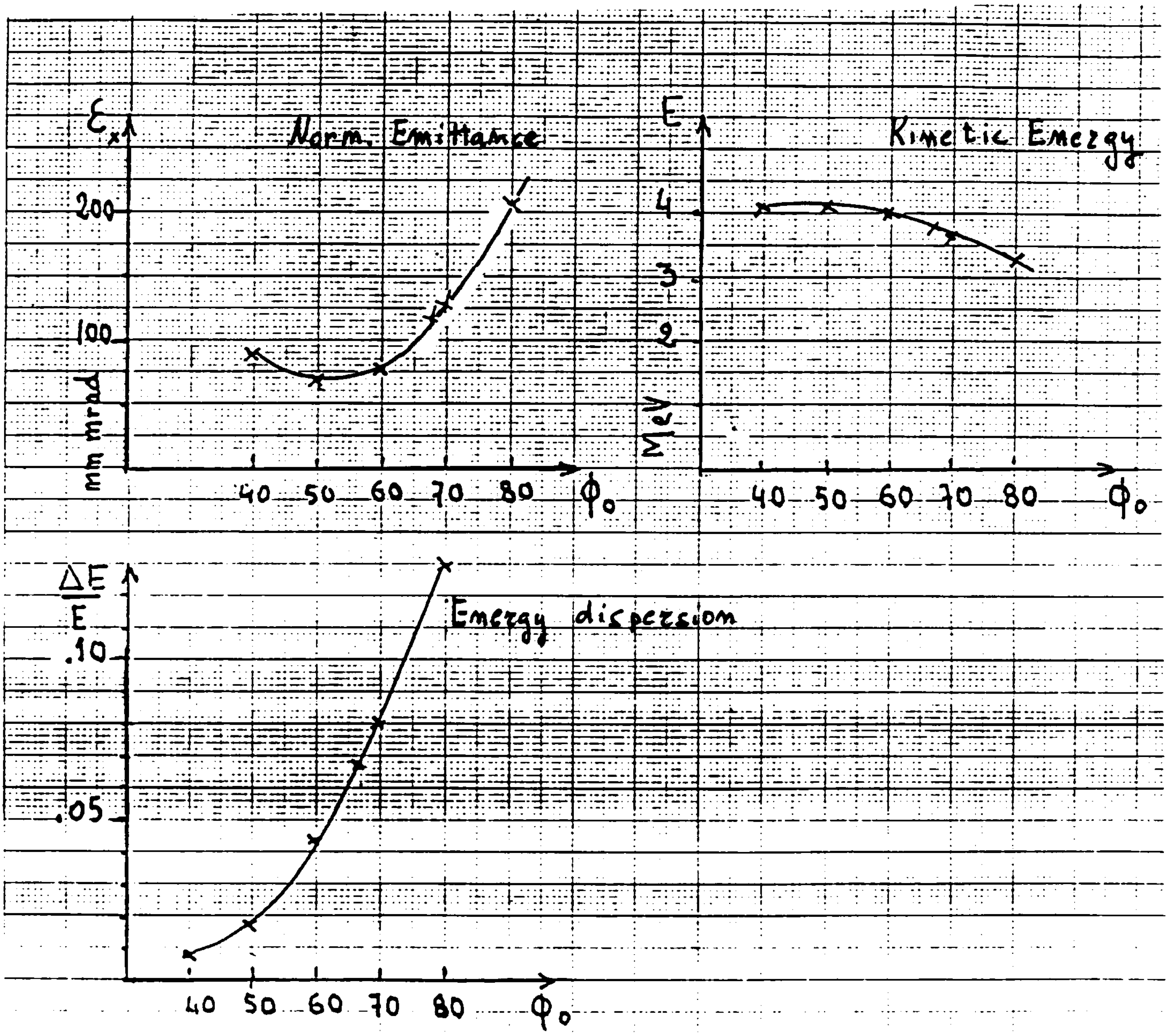

Figure 4: Time evolution of the bunch for $\phi_0 = 50 deg$ and longitudinal and transverse phase space at the end.