Characterization of the longitudinal dynamics of nanosecond electron bunches traveling in a Malmberg-Penning trap

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The diagnostics and control of plasma collective effects play a fundamental role when dealing with high-quality charged-particle beams [1]. The ELTRAP [2] device is able to trap an electron plasma (operating as a Malmberg-Penning [3] trap) and also to perform basic studies on the dynamics of nanosecond electron bunches in the keV energy range. The device is sketched in Fig. 1 on the left. The electrons are emitted by a photocathode illuminated by a pulsed UV laser (wavelength 337 nm, pulse duration $\lesssim 5$ ns, average energy per pulse 400 μJ). The electrons are accelerated by a voltage difference of 1–20 kV imposed between the source and a grounded extraction electrode. Electron bunches with a length of 15–30 cm and a total charge up to ≈ 300 pC are obtained. They travel inside a stack of coaxial hollow conducting cylinders of inner radius $R_W = 45$ mm, at a base pressure of a few 10^{-9} mbar. A highly uniform, axially-directed magnetic field of strength up to 0.2 T, generated by a solenoid placed outside the main cylindrical vacuum chamber, provides radial focusing of the beam.

Earlier experiments making use of a planar phosphor screen (coated with an aluminum layer) both as imaging device [4] and as a charge collector [5], demonstrated a significant spread of the axial length of the bunch at low energies due to space charge effects. The ELTRAP apparatus has been recently upgraded with the aim of exploiting the Thomson backscattering technique, comprising an infrared (IR) laser and an array of photomultipliers, as an additional tool for the diagnostics of bunched electron beams. As an alternative to the charge collector and as a complement to Thomson backscattering, the transport of the bunches is studied here by means of a non-interceptive and non-perturbative measurement based on the current signals induced on the trap electrodes by the crossing of the beam. The charge induced on a cylindrical electrode with length L_A, radius R_W (and enclosed within two infinitely long, grounded conducting cylinders) can be computed using the Ramo theorem [6] (see Fig. 1 on the right) as

$$q_{ind}(t) = \int_0^{2\pi} d\theta \int_0^{R_B} rdr \int_{-L_B/2}^{L_B/2} dz 2en \int_0^{\infty} dk \frac{\sin(\pi k L_A)}{\pi k} \frac{I_0(2\pi k\tilde{r})}{I_0(2\pi k R_W)} \cos[2\pi k(z+z_C)], \quad (1)$$

where $\tilde{r} = \sqrt{r^2 + r_C^2 + 2rr_C\cos\theta}$, $-e$ is the electron charge, I_0 is the zeroth order modified Bessel function, R_B, L_B and n are the radius, axial length and density of the bunch, respectively,

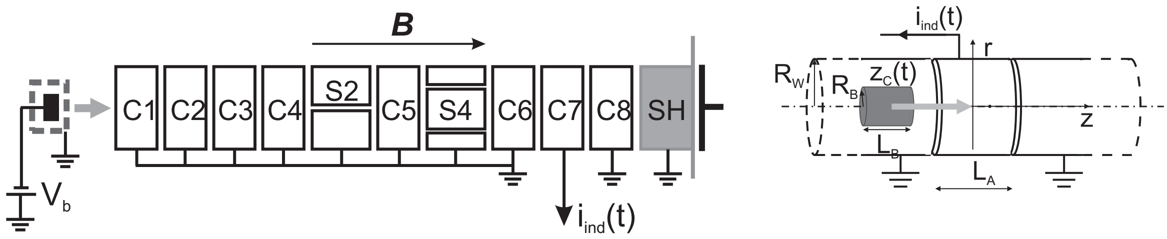

Figure 1: Left: sketch of the ELTRAP apparatus in transmission mode. The electron bunch comes from the photocathode on the left with an energy set by the bias voltage V_b and travels along the axis of the trap, consisting of ten cylindrical electrodes (C1–C8 of length 9 cm, and S2 and S4 of length 15 cm, azimuthally two- and fourfold split, respectively) and a permanently grounded shield SH. One of the electrodes (e.g., C7 in the figure) may be used as antenna. Right: model for the calculation of the induced charge on a cylindrical pick-up.

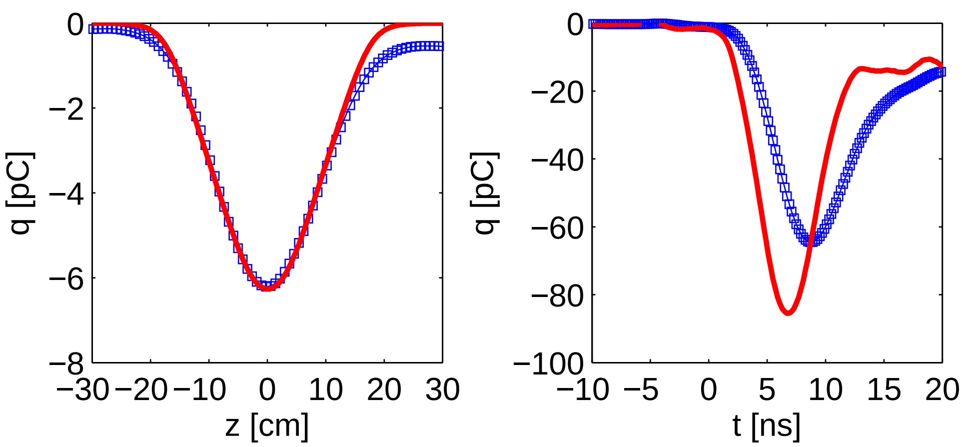

Figure 2: Left: charge signal from a sector of the S4 electrode (blue squares) as a function of the axial coordinate z (centered in the middle of the electrode) and fit according to Eq. (1) assuming $R_B \simeq 0$ and L_B as free parameter (solid red line). Right: charge signal q_{out} from the cylinder C5 (blue squares) and reconstructed induced charge q_{ind} (solid red line). The injection energy of the electrons is $E = 15$ keV.

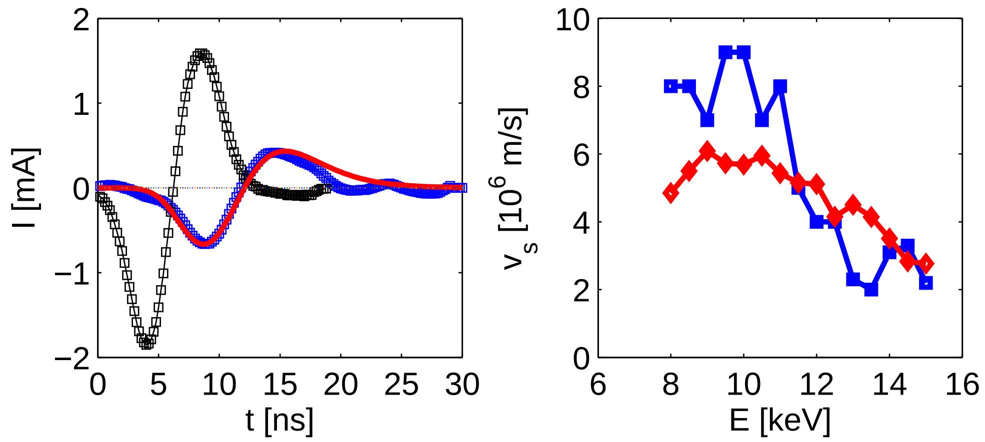

Figure 3: Left: detected current signal for $E = 15$ keV (black squares) and $E = 10$ keV (blue diamonds). The solid red line is the fit for an expanding Gaussian axial bunch distribution. Right: longitudinal expansion velocity of the bunch for different energies estimated for a Gaussian (blue squares) or a flat-top (red diamonds) axial charge distribution.

and the cylindrical coordinates (r, θ, z) are referred to its center of charge $[r_C(t), \theta_C(t), z_C(t)]$. The read-out signal $q_{out}(t)$ is in general distorted by the pick-up parasitic capacitance C, $q_{ind} = \tau dq_{out}/dt + q_{out}$, where $\tau = RC$ is the time constant of the circuit (R = 50 Ω is the input impedance of the oscilloscope used for recording the signal). Assuming a Gaussian time distribution for q_{ind} and estimating its width from a fit of the charge signal detected on a sector of the S4 electrode (assumed of negligible C), one can estimate the capacitance of a cylindrical electrode (C1–C8) from a fit of the experimentally detected signal with the analytic solution for q_{out}, and then reconstruct the actual induced charge signal q_{ind} on it (see Fig. 2). For the estimate of C with this method, a constant length of the bunch (and therefore a constant width of q_{ind}) is assumed, which is valid only at high bunch energies.

Space charge effects leading to a longitudinal spread of the beam along the drift tube are evidenced at low injection energies by asymmetries in the detected current (or charge) signals (see Fig. 3 on the left). The longitudinal expansion velocity has been evaluated to be of the order of a few 10^6 m/s assuming in Eq. (1) $R_B \simeq 0$ and a Gaussian or a flat-top charge distribution of the bunch with a width linearly increasing in time (see Fig. 3). This result is in qualitative agreement with that of a one-dimensional cold-fluid model described in Ref. [7]. The dynamics of the electron beams has been studied also by means of two-dimensional (2D) particle-in-cell (PIC) simulations [8]. A clear spread of the bunch during its transport through a grounded drift tube is found at low injection energies and relatively high bunch currents (see the left and middle plots in Fig. 4). This axial spread turns out to be larger close to the axis, as it is

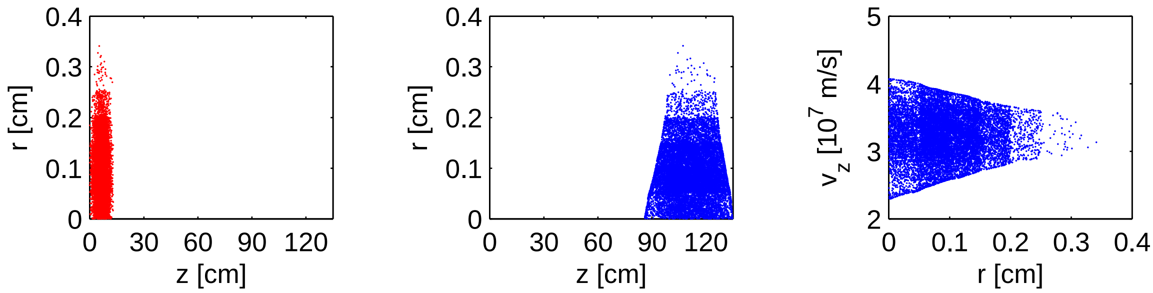

Figure 4: 2D PIC simulation of the dynamics of an electron bunch (with an initial Gaussian distribution in r and z, with a rms radius of 1 mm and a time width of 4 ns) in a drift tube with radius 4.5 cm and length 135 cm (a smaller radial window is shown). The charge of the bunch is 200 pC, $E = 3$ keV and $B = 0.05$ T. A grid of $300(z) \times 90(r)$ points has been used. Left and middle: particle distribution after the injection and just before the exit of the drift tube, respectively. Right: radial distribution of the axial velocity at the exit.

evidenced also from the radial distribution of the axial velocity (see right plot in Fig. 4). The bunch expansion velocities obtained from the PIC simulations are in good agreement with the experimental results.

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