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Experimental Investigation of the Dynamics of Low Energy Electron Bunches in a Malmberg-Penning Trap

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Malmberg-Penning traps, which are usually employed for performing experiments on trapped non-neutral plasmas, are also suited to the study of beams due to presence of multiple probes and diagnostic systems. A previous work on continuous electron beams at very low energy (10–100 eV) was performed in the ELTRAP device [1]. The role of the total beam current in determining abrupt changes in the beam density profile was investigated, together with the formation of coherent structures [2, 3]. The apparatus has been suitably modified in order to investigate plasma effects on the dynamics of short (few ns) electron bunches in the keV energy range. These effects can play an important role in assessing the high quality of beams (e.g, the achievable brightness), which is needed in FELs, gyrotrons, or other electromagnetic wave generators [4]. A direct experimental characterization of these effects may be difficult in high-energy (~ 100 MeV) and ultrashort (few ps) bunched beams. By properly scaling density, current, magnetic field and spot size, similar effects may be measured in ELTRAP on beams with much lower energy but exhibiting an almost identical transverse dynamics of the beams used in these devices. The results are in fact equivalent to those obtained in beams in different regimes if the parameter $\omega_p^2/\gamma\omega_c^2 \propto I/\beta\gamma B^2 r^2$ is kept constant [5], where ω_p and ω_c are the plasma and cyclotron frequencies, respectively, I the beam current, B the magnetic field, r the beam radius and β, γ the usual relativistic factors.

The experimental set-up [1] is shown in Fig. 1-left. A pulsed electron beam is generated by a photocathode source heated at ≈ 1100 K and illuminated by a pulsed UV laser (wavelength 337 nm, pulse duration $\lesssim 5$ ns, repetition rate up to 30 Hz, average energy per pulse 300 μJ, peak power 75 kW). A local magnetic field generated by a Helmholtz-coil pair provides the initial focusing of the emitted electrons. This magnetic field can be raised to 50 G, with a 0.5 G uniformity over a distance of 13 mm from the emitter. The electrons are accelerated by a fixed voltage difference of 1–20 keV imposed between the source and the grounded extraction electrode. Electron bunches with a length of about 15–30 cm and a total charge up to ≈ 50 pC can be obtained. The electron bunch travels inside a stack of coaxial hollow conducting cylinders, kept under ultra-high vacuum conditions (residual gas pressure of a few 10^{-9} mbar) [1]. An

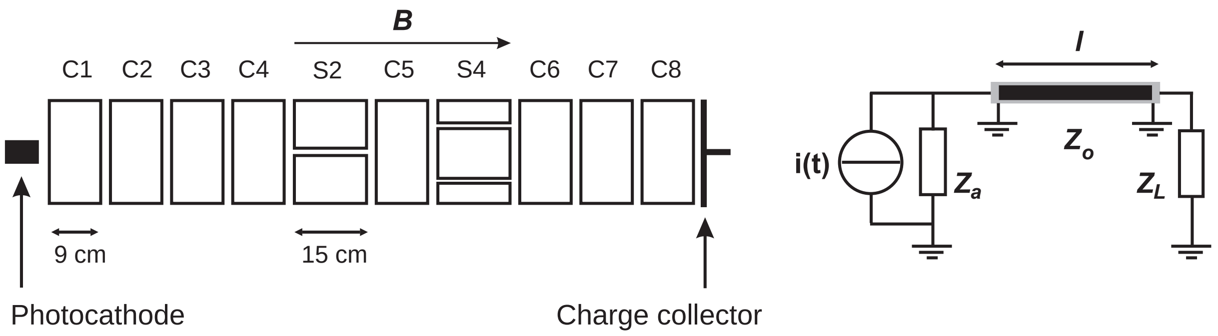

Figure 1: Left: Malmberg-Penning trap ELTRAP in an open configuration. Eight cylinders of length 9 cm and two azimuthally sectored cylinders (with two and four patches, respectively) of length 15 cm are present. Right: Circuital model of the charge collector, where $i(t)$ is the detected current, and Z_a, Z_0 and Z_L are the impedances of the antenna, of the transmission line (of length $l = 2$ m) and of the oscilloscope, respectively.

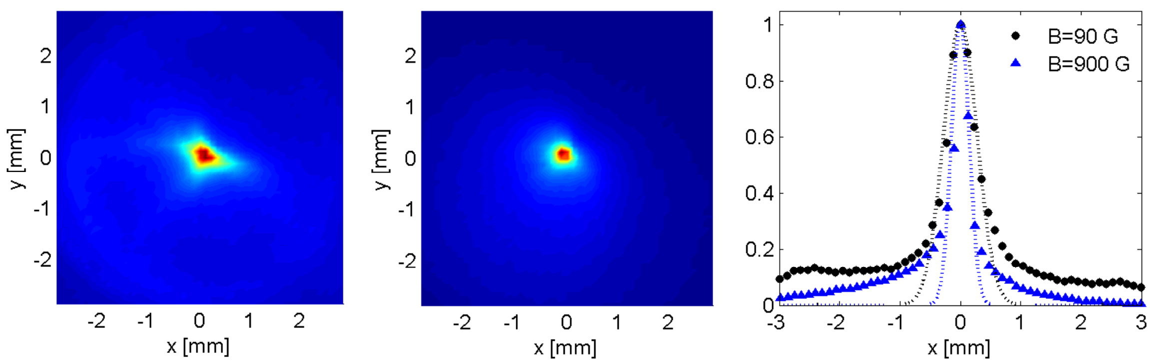

Figure 2: Spots of a 6 keV beam at $B = 90$ G (left) and $B = 900$ G (center). Right: Profiles of the beams (horizontal cut in the center). The FWHM is 0.65 mm at $B = 90$ G and 0.34 mm at $B = 900$ G, respectively. The dotted lines are Gaussian fits with the same FWHM.

axial magnetic field B up to 0.2 T provides radial focusing of the beam. The electrons finally hit a charge collector consisting of a planar P43 phosphor screen (diameter 110 mm), coated with an aluminum layer. The screen produces a ≈ 1 ms light pulse, which can be recorded by a Charge-Coupled Device (CCD) camera. This imaging system gives information on the transverse (axially integrated) beam density. This has been obtained by varying the source parameters (accelerating potential difference, strength of the focusing magnetic field at the source, photoelectric emission in conjunction with thermionic emission) and the external magnetic field strength. Examples of spots are shown in Fig. 2.

The screen can be used also as a charge collector. The charge deposition determines the formation of an electric signal across the overall load impedance of the plate, which is recorded by a 1 GHz analog bandwidth digital oscilloscope with a $Z_L = 50\ \Omega$ input impedance. The data acquisition is triggered by the laser through a TTL signal, whose rising front corresponds to the presence of the optical output. The trigger signal has a small jitter of 0.5 ns and it is generated a few ns before the bunch has reached the charge collector. Even if the voltage signals recorded by the oscilloscope are irregular because of the impedance mismatch between the probe and the data acquisition system, with a proper data post-processing analysis it is possible to obtain information on the bunch length, depending on the beam injection conditions [6]. The detection system is equivalent to a current generator $i(t)$ and a load impedance consisting in the combination of the impedances of the antenna (Z_a), of the transmission line (Z_0) and of the digital oscilloscope (Z_L); see Fig. 1-right. Assuming that the electron beam travels with a constant axial velocity v and it has a Gaussian axial density profile, the input current is $i(t) = i_0 \exp(-t^2/2\sigma_t^2)$, with $\sigma_t = \Delta L/2v$ and ΔL the bunch length. The output signal therefore reads

$$V(t) = \frac{\sigma_t i_0}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left(j\omega t - \frac{\omega^2 \sigma_t^2}{2}\right) \left[\frac{\cos(\omega l/v_p)}{1/Z_L + j\omega C_a} - jZ_0 \sin(\omega l/v_p)\right] d\omega, \qquad (1)$$

where C_a is the capacitance of the collector with respect to ground, v_p the phase velocity of the signal in the transmission line of length l, and ω the frequency. The analysis of Eq. (1) shows that $\zeta \equiv |V_{max}/V_{min}|$, V_{max} and V_{min} being the first maximum and minimum of $V(t)$, depends on the time width σ_t of the beam [6]. A set of experimentally obtained voltages (averages over 50 signals, after subtraction of the noise generated by the laser discharge within the laser cartridge) is shown in Fig. 3-left for different values of the beam injection energy. The bunch length ΔL extracted from the analysis of ζ is shown versus the beam energy E in Fig. 3-right.

The results obtained for the higher beam energies (8–10 keV) are in agreement with a constant pulse spread (see continuous line in Fig. 3-right) while at lower energies an increased bunch length is found. Such a behavior is due to deformations experienced by the beam during the transport towards the charge collector, which can be caused either by intrabeam collisions or space charge effects. The typical collisional time τ_c of intrabeam scattering phenomena [7] can be estimated assuming for the beam temperature the cathode temperature of the order of 0.1 eV. The measured beam densities range between 10^8 and 10^9 cm^{-3}, yielding a τ_c from 320 ns to 1.40 μs. The corresponding times of flight are one order of magnitude smaller, ranging from 30 to 100 ns, therefore ruling out collisions as a significant cause of beam spread. Conversely, the plasma period $2\pi/\omega_p$ turns out to be always $\lesssim 10$ ns, indicating the influence of space charge. An estimate of the deformation of the beam profile under the effect of the bunch self-field can be carried out, e.g., using the one-dimensional cold-fluid model described in Ref. [8]. The spread of the bunch ends is evaluated as $c_s\tau_f$, where c_s is the speed of the space-charge waves within

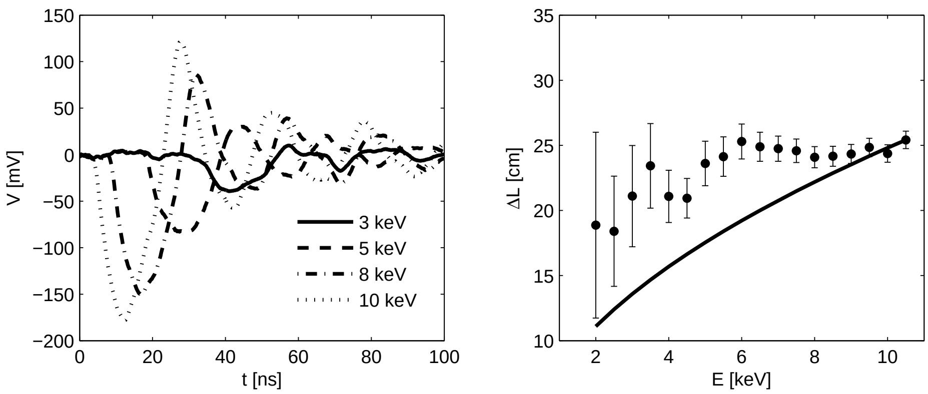

Figure 3: Left: Voltage signals for different beam energies ($B = 330$ G). Right: Estimated bunch length (the continuous curve is the theoretical $E^{1/2}$ trend for a constant beam length). The error bars take into account the electronic noise measured in the absence of the laser discharge and the standard deviation of the mean over the acquired voltage signals.

the beam and τ_f the time of flight. Using the parameters of the experiment, this quantity turns out to be of the order of 3–8 cm, in good agreement with the measured values.

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