Thomson backscattering diagnostics of nanosecond electron bunches traveling in a Penning-Malmberg trap

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Thomson scattering has been since several years an established tool for the diagnostics of magnetically confined high-temperature plasmas. More recently Thomson backscattering of intense laser radiation from relativistic electron beams has been used as a source of coherent X-rays [1]. We present here an application of Thomson backscattering to charged particle beams. Indeed, plasma collective effects play a key role in high-quality beams of charged particles and therefore the control and diagnostics of these collective behaviors are of fundamental importance to achieve and maintain the desired beam properties [2]. We have recently upgraded the ELTRAP (ELectron TRAP) [3] set-up with the aim of demonstrating the use of a Thomson-backscattering based technique as a diagnostic tool for a space-charge dominated nanosecond electron beam in the 1-20 keV energy range.

The ELTRAP device is a Penning-Malmberg trap, i.e. a cylindrically symmetric ultra-high vacuum confinement volume where the combination of a longitudinal, highly homogeneous magnetic field and electrostatic potentials set on a stack of copper cylinders guarantees a long-time storage of a nonneutral electron plasma. The device has been used so far for the study of collective modes on low-temperature electron samples [4]. The sketch in Fig. 1 illustrates the modifications implemented in the set-up to perform the Thomson backscattering experiment and the main experimental concept. A pulse of duration ≤ 4 ns from a 337 nm ultraviolet (UV) laser impinges on a thoriated tungsten cathode. The target is held at a negative potential between 1 and 20 kV and the photoemitted electrons are extracted by the cathode region through a hole in the grounded enclosure. Our previous subsidiary characterization of the electron bunches by means of destructive [5] and non-destructive [6] methods has shown that as the electron bunch travels through the trap, the longitudinal magnetic field $B \leq 0.2$ T fully compensates the radial space-charge expansion so that the bunch diameter is below 1 mm, whereas a considerable axial expansion takes place at low bunch energy. Assuming a cylindrical, homogeneous electron bunch of energy 15 keV we obtain a density of about $4.3 \cdot 10^8$ cm^{-3}. A $4-6$ ns infrared (IR) 1064 nm laser pulse with an energy of 0.96 J is shot through a glass window into the vacuum

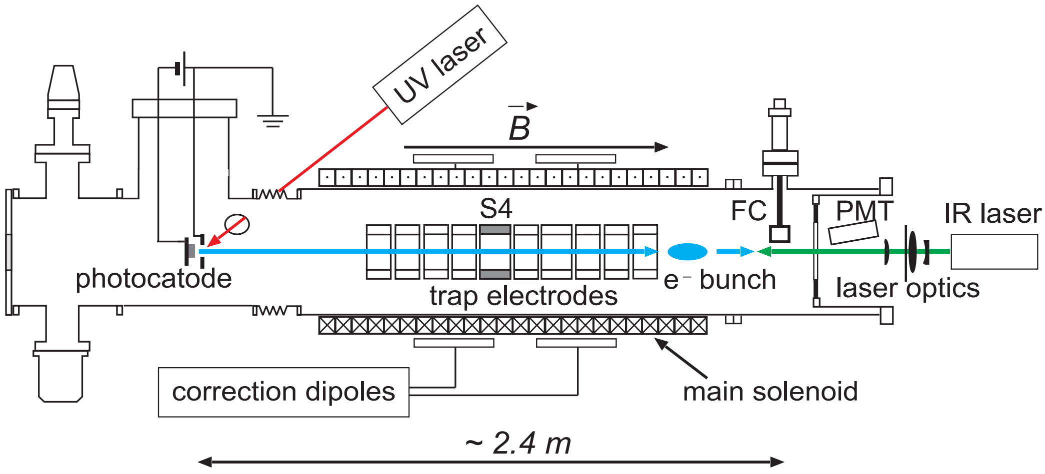

Figure 1: Sketch of the experimental set-up. A photocathode is hit by a 4 ns ultraviolet (UV) laser pulse. The electron cloud thus generated is extracted at energies in the $1-20$ keV range and is transported along the longitudinal magnetic field of strength B$\leq$ 0.2 T until it collides with a counter-propagating $4-6$ ns infrared (IR) laser pulse, focused through a viewport in the set interaction point. The backscattered radiation is detected by a photomultiplier (PMT). Time and space coincidence are obtained by measuring induced signals on the S4 trap electrode, adjusting the bunch transverse position with two orthogonal sets of correction magnetic dipoles (2D beam scanner) and matching bunch and IR beam with a removable Faraday cup (FC).

chamber in the opposite direction with respect to the electron bunch. The backscattered radiation is in the visible range and a fraction is detected by a photomultiplier (PMT) equipped with a set of IR and UV filters. Provided that a sufficient number of photons is detected, the intensity, mean frequency shift and frequency distribution of the scattered radiation can yield information on the density, energy and energy spread of the electron bunch.

The main technical difficulties in the present experiment are represented by the determination of the most suitable interaction point, the stray light reflected within the vacuum chamber and the severe constraints set by the time and space coincidence of electron and laser pulses. Our calculations set the present optimal interaction point at a distance of 10 cm from the PMT. Due to the short duration of the electron-laser interaction, the synchronization must be within 1 ns. Therefore the delay required between the emission of the UV and IR laser pulses has been determined calculating the travel time of the electric signals in the cables with a reflectometric technique and estimating the time of flight of both the lasers and the electron bunch. The time coincidence can be verified *a posteriori* measuring the time delay between the electric signal induced by the bunch when it passes through the S4 electrode and the signal produced by an IR

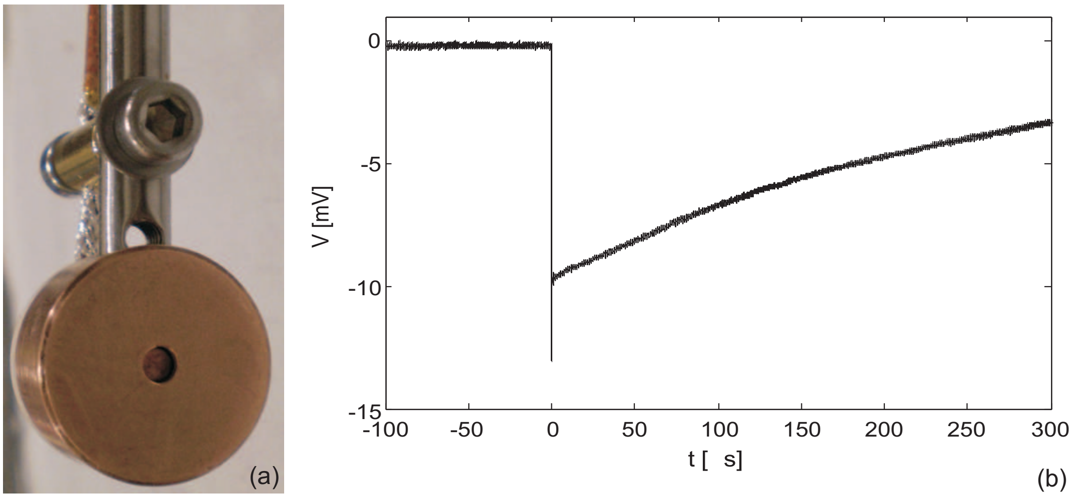

Figure 2: (a) Photograph of the coaxial Faraday cup (FC). The 20 mm diameter grounded shield is mounted on the shaft of a manually-operated linear actuator. The circular hole and the central cylindrical conductor have a diameter of 3 mm. (b) Resistive-capacitive (RC) discharge signal generated by an electron bunch impinging on the FC and read on a digital oscilloscope with a load of 1 MΩ.

laser detector.

Small misalignments between bunch injection and trap magnetic axes cause the electron pulse to reach the interaction axial position with a transverse offset up to few millimeters. This mismatch can be corrected with the use of two orthogonal sets of magnetic dipole coils. A Faraday cup (FC) with an active area of diameter 3 mm mounted on a linear actuator can be moved down to the trap axis and the signal due to the electron bunch impinging on the FC is read on a digital oscilloscope. As the bunch transverse position is varied through an automated or manual scan of the electric currents in the dipole coils, the lowest value of the voltage signal (see Fig. 2) determines best centering of the beam. The IR laser can be aligned with the central point of the back side of the FC. The device is then removed from the axis to perform the experiment.

In order to estimate the minimum detectable electron density we evaluate the set-up sensitivity, i.e. the amplitude of the PMT signal for which the signal-to-noise (S/N) ratio is one. The noise is measured experimentally and includes a coherent component induced by the UV and IR laser discharges, the electronic noise and the stray light reflected within the vacuum chamber which is not completely filtered out. The coherent part can be averaged and subtracted and Fig. 3 shows the remaining noise, where the increase after 33 ns is due to the stray light. The

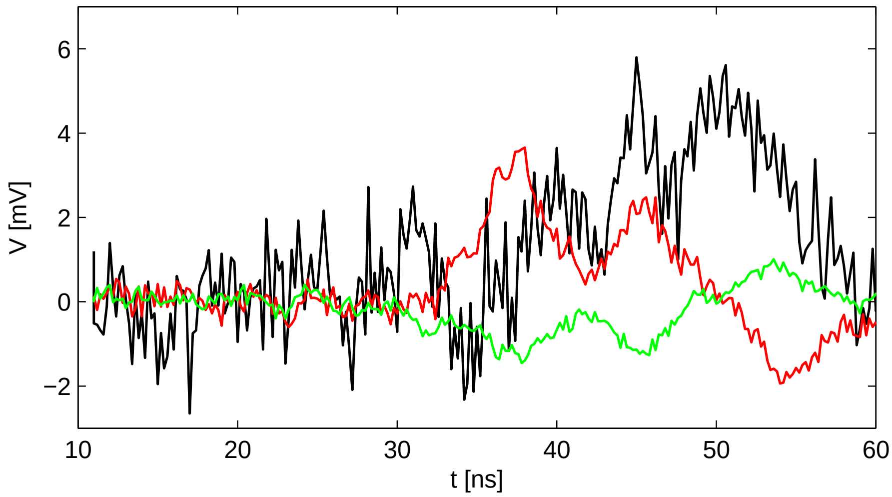

Figure 3: Incoherent noise signal. The residual uncorrelated background noise is obtained subtracting the time-averaged coherent noise from the photomultiplier signal. The gray, red and blue curves show the incoherent background after averaging and subtracting 0.1, 1 and 5 s of coherent signal. After 33 ns the noise level increases due to the stray light of the laser reflected within the vacuum chamber.

backscattering signal is expected between 28 and 33 ns. Considering these values and a PMT gain of $6 \cdot 10^4$ (limited by the noise level itself) one can determine the number of photons necessary to obtain S/N= 1 and in turn, with a bunch energy of 15 keV the required density, i.e. $3.6 \cdot 10^{10}$ cm^{-3} for an integration time of 5 s. Future optimization is oriented to the improvement of the S/N ratio through a further noise reduction and an increase of the bunch density.

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