Experimental investigation of the dynamics of space-charge dominated, traveling and confined electron plasmas in a Penning-Malmberg trap

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When dealing with high quality charged-particle beams, the control of plasma collective effects plays a very important role. E.g., space-charge phenomena tend to break the bunch spatial coherence and therefore put a fundamental limit on the beam brightness obtainable from charged particles' accelerating devices [1]. The Penning-Malmberg trap ELTRAP [2] has been modified in order to perform studies on the dynamics of space-charge dominated, 1-20 keV energy, 4-5 ns electron bunches, produced by a photocathode source illuminated by a pulsed ultraviolet (UV) laser. The bunch transverse focusing is maintained by the uniform magnetic field up to 0.2 T of the device. In order to characterize the longitudinal dynamics of the electron bunches, different diagnostics were used like electrostatic pick-ups as well as an optical system based on a phosphor screen and a Charge-Coupled Device camera [3, 4]. In particular, the presence of longitudinal space-charge effects was evidenced even at relatively low bunch densities of a few 10^8 cm^{-3}. More recently, a Thomson backscattering diagnostic apparatus has been implemented (see Fig. 1), based on a 5 ns, 1064 nm, Nd:YAG laser pulse interacting with the traveling electron bunch. For beam energies of the order of 10-20 keV, the backscattered radiation turns out to be in the visible range, and is detected with a photomultiplier (PMT). With respect to alternative electrostatic diagnostics of the beam, the main advantages of the backscattering technique are its non-perturbative nature, and the potential to offer a wealth of information on, e.g. the bunch density and density profile from the intensity of the scattered radiation as well as the beam longitudinal energy and energy spread from the radiation spectrum. The main limitation is the necessity for densities that are generally higher that those required by more conventional diagnostic tools.

Although conceptually simple, the realization of the Thomson backscattering experiment presents unfortunately several complications. The matching of electron and laser pulses (both cross sections being below 1 mm) is guaranteed by an automated steering system that locks the bunch position onto the set interaction point [5]. The short duration of both laser and electron pulses, together with the UV laser jitter, requires an accurate timing and monitoring of the
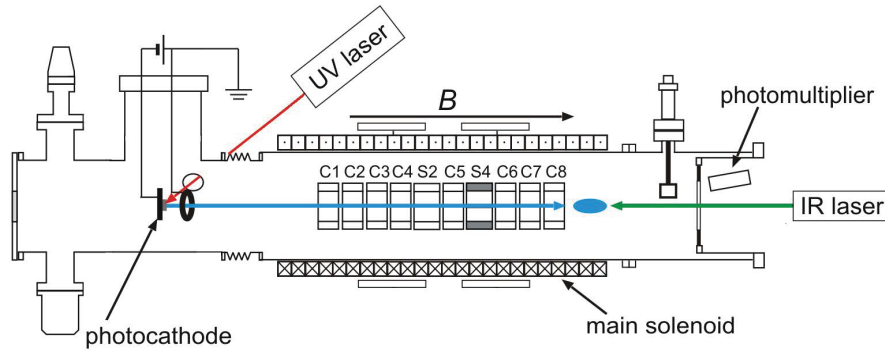
Figure 1: Sketch of the Thomson backscattering diagnostic set-up. The photoemitted pulsed electron bunch is extracted at an energy of 1-20 keV and focused by the axial magnetic field B of the trap. The radiation of an infrared (IR) laser is focused to the interaction point with the bunch by a suitable optical system. The scattered radiation is filtered and detected by a PMT.

time coincidence. A more critical issue is represented by the very small scattering cross section, combined with the presence of stray light noise limiting the photon detection capabilities. As for the injection of the IR radiation and the detection of the scattered photons, suitable optical and filtering systems have been introduced in order to reduce the stray light. Nonetheless, this remains the most stringent limit to the signal-to-noise (S/N) ratio (the noise includes also the coherent disturbance produced by the IR and UV laser discharges and the electronic noise). The present sensitivity of the apparatus corresponds to a detectable density of $\simeq 3 \cdot 10^{10}$ cm^{-3} [5], which is beyond the yield of the present source ($\leq 10^9$ cm^{-3}).

A series of upgrades aimed at the increase of the S/N are presently under way. In particular, a more powerful UV laser, with reduced jitter has been acquired for the electron source. To limit the effect of the reflections/re-emissions from the vacuum chamber surfaces, a suitable light shield has been designed. The shield is essentially a disc with a central hole allowing the beam transmission and hence the laser-bunch interaction, while most of the light reflected by the chamber walls is prevented from reaching the PMT (see Fig. 2). Finally, an optimization of the detection electronics may be performed by, e.g., using a low-noise amplifier for the PMT signal. The reduction in the overall noise level would yield the further advantage of increasing the (presently limited) gain of the PMT.

In addition to the diagnostics for bunched electron beams, new manipulation tools for confined electron plasmas are being developed in ELTRAP. The generation of an electron plasma under ultra-high vacuum conditions by means of a low-power radio frequency (RF) drive in the MHz range applied on one of the trap electrodes has been previously demonstrated [6]. The
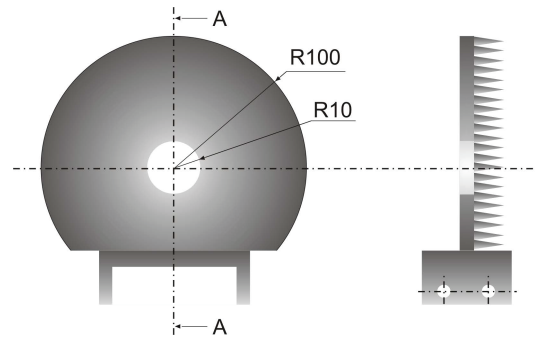
Figure 2: The shield consists of a disc with a 20 mm hole mounted on the trap stack holding bar. Beam transmission is possible through the hole, while the bulk of the radiation reflected within the vacuum chamber is blocked. The back side is structured with deep grooves to "trap" light by multiplying the number of reflections.

design of a new microwave heating system is under way. This will allow the extension of the RF studies to the GHz range and in particular the production of a denser and more energetic electron plasma via cyclotron resonant excitation. The microwave radiation will be injected into the trap by means of a coaxial waveguide transition coupled to one of the internal cylindrical electrodes. This solution is required to avoid obstruction of the trap ends.

In order to optimize the power transmission to the confinement region of the electron plasma, electromagnetic simulations have been performed with COMSOL Multiphysics, a commercial finite element simulation software package. Results for the injected power density are shown in Fig. 3. The power fraction entering the trap region, computed for different positions of the RF transition along the trap axis and different RF frequencies is reported in Fig. 4. The frequency
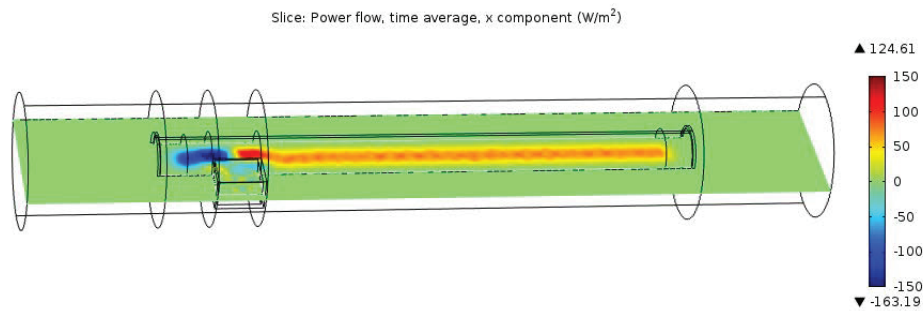

Figure 3: Power density transmitted from a rectangular waveguide to the region inside the set of cylindrical electrodes of the trap, for a frequency $\nu = 2.9$ GHz. The real geometry of the apparatus is used, with a length of the electrodes' stack of $\simeq 100$ cm, and an internal radius of the cylinders of 4.5 cm. The radius of the surrounding vacuum chamber is 12.5 cm.
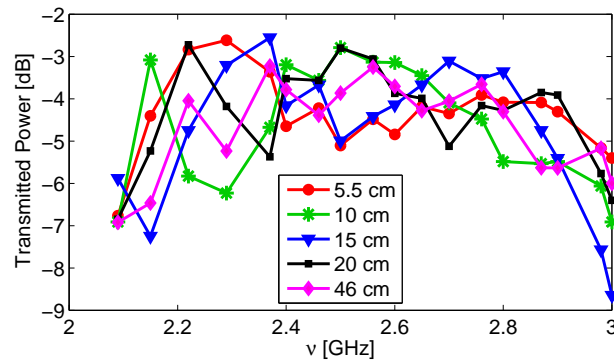
Figure 4: Power fraction entering the trap region *vs* the frequency of the injected wave, for different distances of the RF transition from the trap end.

range has been chosen taking into account the cutoff set by the geometry of the electrode stack (cylindrical waveguide) and the achievable magnetic field. The dimensions of the RF transition must also fit the geometrical constraints of the trap, i.e. electrode size and vacuum chamber radius. A prototype is being designed and RF transmission will be measured on a test bench. Then the system will be installed in the device, opening up the possibility to study, e.g., the interaction between the confined plasma and a traveling electron bunch.

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