

PLANAR ELECTRON SOURCES AND THE ELECTRON TRAP ELTRAP

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Abstract

A Malmberg-Penning trap, named ELTRAP, installed and operated at the University of Milan, is briefly described; trap length ranges from 10 cm to 1 m; an uniform magnetic field confines electron radially. Several experimental regimes were investigated with the internal CW planar electron source: plasma, beam-plasma, beam, depending on the injection/extraction method chosen. Dynamics of intense electron beams may be simulated in this machine. Evolution of electron vortices and virtual cathode formation is documented. Machine upgrading are discussed: an external laser pulsed electron source will make also experiments of bunch expansion possible; larger plasma will be studied with planar sources under construction.

INTRODUCTION

Malmberg-Penning traps represent a simple, yet effective and flexible, device for the accumulation of electron beams, making a cylindrically shaped cloud, where several non-linear and self-organization effects can be conveniently studied [1].

The design of ELTRAP machine, now installed at University of Milan, aimed at providing a large size Malmberg-Penning trap (inner electron diameter $2r_w = 90$ mm, plasma length up to 1 m), and an adequately uniform field. Interesting results, obtained with a standard electron source (diameter $2r_f = 25$ mm), and design issue and development of a larger source (70 mm) are here described (see Fig. 1); these thermionic sources operates inside the main solenoid field. Another e^- source, capable of ns bunch thanks to laser drive, is being built, and will be mounted externally (see Fig. 2).

Filamentation and other major space charge effects of intense e^- beams, found for example in rf photoinjectors (beam energy 1 MeV, current 100 A), are easily studied in this machine, notwithstanding the low voltage (0.01 – 0.1 kV), by keeping the same perveance order.

Along trap axis z , electrons are confined by an electric potential $\phi(x, y, z; t)$, whose z profile is adjustable by 12 electrodes; in particular the negatively biased electrode (-80 V) that reflect electrons are named plug electrodes; $\phi = 0$ is by convention the vacuum chamber, usually connected also to central electrodes. Radial motion is effectively prevented by the solenoid field $\mathbf{B} \cong B_c(z)\hat{z}$, which adds a slow drift $\mathbf{v}_d = (\mathbf{E} \times \mathbf{B})/B^2$ to the electron motion, where $\mathbf{E}$ included the self-fields, which dominate the rotation.

Note indeed that the internal sources are immersed in the solenoid field $B_c(z_s) \cong B_0$, where z_s is the source position and B_0 is the middle plane field $B_0 = B_c(0)$, so Busch rotation is negligible even at large radius [2]; the external source has conveniently small radius (≤ 2.5 mm and of laser spot).

The internal source is a filament (or a spiral) directly heated by a current I_f . Let I_s be the total current leaving the source assembly and V_b the source center applied voltage: $V_b = -\phi(0, 0, z_s)$. Let us define the filament voltage $V_f = \phi(0, r_f, z_s) - \phi(0, 0, z_s)$. Even with a small source $r_f = 12.5$ mm, a large beam perveance P_b is typically obtained ($P_b = 5$ microperv with $I_s = 0.4$ mA and $V_b = 20$ V and $V_f = 3$ V).

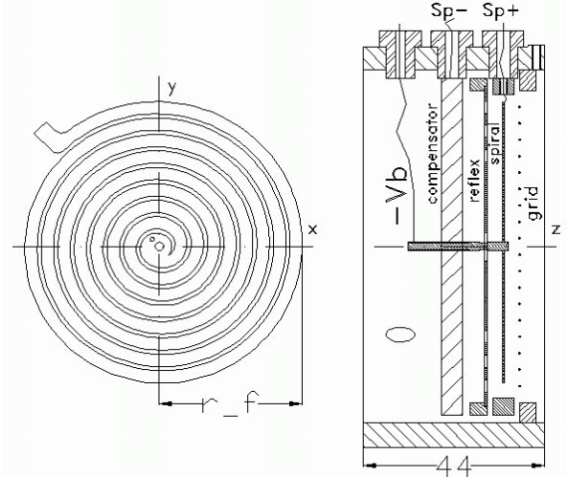


Figure 1: Internal e source with planar spiral emitting surface of radius r_f ; heating current I_f flows from contact SP+ to SP- via the spiral and the compensator; V_b is also sensed.

BEAM PRODUCTION AND INJECTION

Basic theory of evolution of stored plasma (vorticity-line density equivalence, 2D inviscid motion) were discussed elsewhere [1], so we consider here the injection phase, when the first plug is off. Even if current is emitted in all directions, note that $j_r \ll j_z$ for the presence of B_0 ; let us assume that B_0 is strong enough so that the electron gyroradius is negligible compared to r_f and r_w . Near the source, as a first approximation, it is convenient to average over the azimuthal coordinate ϑ , since the electrodes are cylindrical and $B_\vartheta = 0$; let $\bar{g} = (1/2\pi) \int d\vartheta g$ and $\tilde{g} = g - \bar{g}$ for any g . Moreover, let be $j_s(\vartheta, r)$ the z -component of the current emitted by source and $j_a = \bar{j}_s$; representing

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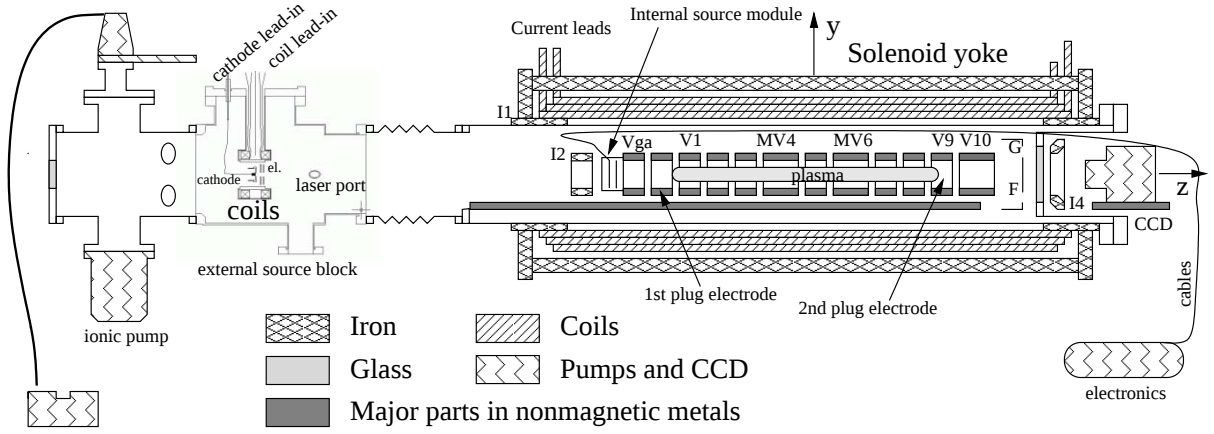


Figure 2: Experimental set-up general plan (only one source plug-in or the external source can be used at a time); vertical section. I1, I2, I3 and I4 are shims to improve $\mathbf{B}$ uniformity, MV4 and MV6 sectored electrodes, F the phosphor screen with its guard ring G. A UV laser, making a 40° angle with z axis enters through a CF16 quartz window and via a laser port and some holes in the extraction electrodes (el.) reaches a pre-heated cathode

j_s faithfully would require actually to conform to the filament shape, while $j_a(r)$ is roughly uniform: $j_a = -j_{th}$ for $r < r_f$. Similarly the average $\phi_a = \bar{\phi}|_{z_s}$ of the potential at the source is simply determined by the Ohm law applied to the filament as

$$\bar{\phi} \cong \phi_a(x, y) = -(V_b - V_f r^2 / r_f^2) \quad (1)$$

The Poisson equation and continuity equation give

$$\Delta \bar{\phi} = -\frac{e \bar{n} F}{\epsilon_0} = \frac{j_{th} F \sqrt{m}}{\epsilon_0 \sqrt{2e(\bar{\phi} - \phi_a)}} \quad (2)$$

for $\bar{\phi} > \phi_a$ and $r < r_f$; and 0 otherwise. The reflection factor $F(r)$ is $F = 1$ if the beamlet is not reflected (that is, travels along z until it is absorbed by the phosphor screen) and $F = 2$ if it is reflected (for example, this happens always if the end plug is on). Eq. 1 and 2 and F and electrodes voltages define a nonlinear elliptic problem for ϕ . For example, requiring a uniform beam density in the central drift region (where $\phi = 0$ at $r = r_w$) implies $\phi - \phi_a = \text{const}$ (in other words equal speed $|v_z|$); so $\phi = -V_c + V_f(r/r_f)^2$ for $r < r_f$. Then we get $V_c = -V_f[1 + 2 \log(r_w/r_f)]$ and a matching condition

$$j_{th} = j_{th}^m = \frac{4\epsilon_0 V_f}{F r_f^2} \sqrt{\frac{2e[V_b - (1 + 2 \log(r_w/r_f)V_f)]}{m}}, \quad (3)$$

similar to a Child-Langmuir condition, for the average thermionic current, with the typical power $V^{3/2}$ scaling in the voltages.

Further analysis shows that if $j_{th} < j_{th}^m$ the beam speed is higher at the center; while if $j_{th} \gg j_{th}^m$ a virtual cathode and a hollow beam are formed. In that case, Eq. 3 may show an hysteresis effect if F becomes 2. Note that grid has an auxiliary role: grid speeds up the beam after emission, but, since energy is conserved, it can not change the speed of beam inside the central drift electrode and therefore the eq. 3 match.

The vortex evolution region

Especially in the case of an hollow beam, the azimuthal perturbation (induced by grid and source asymmetry) may grow along z , indeed vortices are visible on the phosphor screen.

If all electrodes are held to $\phi = 0$, the convenient first approximation is $\partial_z E_z \cong 0$, so vorticity-density relation is recovered (that is $\zeta = \text{curl}_z \mathbf{v} \cong en/\epsilon_0 B_0$) and in stationary regimes

$$\partial_z n = -\frac{\mathbf{v}_\perp}{v_z} \cdot \nabla n, \quad \mathbf{v}_\perp = \frac{\mathbf{B} \times \text{grad} \phi}{B_0^2} \quad (4)$$

which gives vortex evolution with z . In particular, screen display depends on $L/(v_z B_0)$, with $L = z_p - z_s$ and z_p the phosphor position.

Internal planar source

It is easily shown (for example [3], Eq. 1 and 2) that generating a large radius thermionic plasma ($r > 2$ cm) with a reasonable power $P_f = I_f V_f < 200$ W implies a low work function $\phi_e < 2.5$ eV; that requires some cathode development. Fairly satisfying results were obtained with W/Ce filaments, limited to a few turns. On the other side, large planar spirals made of porous tungsten were built, and several impregnation methods are being considered (similar to the usual type B, a mixture of barium and calcium aluminates, [4], $\phi_e \cong 2$ eV), also in consideration of the particular geometry.

The planar source is to be mounted inside a 44 mm long copper cylinder, which fits into one end of guard electrode Vga; so source heat distributes on a large surface, as verified with the 25 mm diameter source, which has the same mounting interface. The maximum grid transparency reaches 97 %. Some transparencies is also lost, when additional supports to prevent sagging of the spiral are mounted.

Laser enhanced source

In the laser enhanced source concept [6], a laser impinges onto the surface of a thermionic emitter, heated at $T_s \cong 800^\circ\text{C}$, below its operational temperature T_o ($T_o = 1000$ to 1200°C in the design example of type B-311 cathode). This surface condition enhances efficiency of photoelectric emission, so that moderate energy (0.3 mJ) lasers are required for reasonable charge $\int dt I_s \cong 50$ pC. Due to small source radius, commercial dispenser cathodes are available and use limited power ($P_f = 15$ W at $T_o = 1200^\circ\text{C}$).

The cathode is placed in the middle of an Helmholtz coil pair, where $z' = 0$; a magnetic field $B_1(z')$ is still useful to focus electrons at the begin of the acceleration gap; B_1 can be raised to 500 G, with a 0.5 % uniformity over a distance $z' < z_1 = 13$ mm from cathode. By reversing current in one coil, $B_1 \cong b_1 z'$ with $b_1 \cong 100$ G/cm may also be obtained.

For this source the operation voltage is much higher $V_b \cong -10$ kV, so that longitudinal bunching is well preserved. The cathode is covered by an approximate Pierce electrode, and two anodes complete the triode arrangement, for flexibility of operation. Relation between I_s , B_1 and V_b will be studied first; for example it is expected that increasing B_1 limits the transverse space available to electrons, and therefore I_s .

EXPERIMENTAL REGIMES

According to the temporal schedule of the plug electrodes, we have three regimes. In the plasma regime, the first plug is held off ($\phi = 0$) temporarily, so that electrons travel through all electrode to the second plug, and are reflected back; turning the first plug on separates the stored plasma from the electron source. With particular tuning of V_b , I_s and B_0 transient instabilities may be observed with sectored electrodes pick-ups [5]. By turning the second plug off after a prescribed time t_s , the stored electrons are dumped on the phosphor screen, where line density profile $n_s(x, y; t_s)$ is measured by scintillation and a CCD camera and total charge Q_s by a calibrated amplifier. Changing t_s allows to reconstruct a movie of the n_s evolution; coherent structure motion and long confinement times $\tau_s \equiv -1/(d \log Q_s / dt_s)$ are usually observed [1]. Analogy of structures with meteorology and with astrophysical plasma is striking.

The beam-plasma regime is obtained by leaving the first plug off and the second plug on continuously: so electron travels up the second plug, are reflected back, and lost through the source, while the self-consistent potential ϕ keep memory of the plasma evolution (eq. 2 or its 3D analogue). Instabilities and particular bands of V_b values can be clearly related, in purely stationary regimes. Since no electron may reach the phosphor screen, up to now the only diagnostic are the electrode pickups [7].

In the beam (or drift) regime, both plugs are held off continuously. Depending on I_s , a virtual cathode may form,

which lead to an hollow beam (eq. 3). From the phosphor screen image, structures of the beam density $n_b(x, y, B_0)$ are found; thanks to eq. 4, decreasing B_0 is roughly equivalent to increasing the drift length L or the transit time t_t . Evolution of n_b with t_t can be rapidly observed, also thanks to improvements in CCD read-out (see Fig. 3).



Figure 3: Vortex and hollow beam formation, before $B_0 = 500$ G is decreased slowly, with $j_{th} = 2.2$ A/m², and $L = 1.1$ m; full movie at Ref. [7]

Simulation of these instabilities and structure with PIC (particle in cell) codes is described elsewhere [8]. Before a complete theoretical systematization of results, the question of accumulated ion density should be raised.

We developed an experimental technique, based on 'clearing fields': between plugs, E_z is not held zero always, but is pulsed to a few V/m, for periods from $t_p = 100$ to 900 ms long, comparable to instability rising times. In other words, $\phi \cong a_0(t) + a_1(t)z$ with $a_0, a_1 L \ll V_b$, so that perturbation of electron motion is small [in particular the bouncing period t_b variation $\delta \log t_b = O(a_0/V_b)$ can be zeroed], but ions are pushed into the plugs, where they are separated and shielded from electron self-fields. Instabilities are largely affected and often suppressed, which is a preliminary evidence of ion role in this instabilities.

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