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Generation of quasi continuous-wave electron beams in an L-band normal conducting pulsed RF injector for laboratory astrophysics experiments

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We report on an approach to produce quasi continuous-wave (cw) electron beams with an average beam current of milliamperes and a mean beam energy of a few MeV in a pulsed RF injector. Potential applications are in the planned laboratory astrophysics programs at DESY. The beam generation is based on field emission from a specially designed metallic field emitter. A quasi cw beam profile is formed over subsequent RF cycles at the resonance frequency of the gun cavity. This is realized by debunching in a cut disk structure accelerating cavity (booster) downstream of the gun. The peak and average beam currents can be tuned in beam dynamics simulations by adjusting operation conditions of the booster cavity. Optimization of the transverse beam size at specific positions (e.g., entrance of the plasma experiment) is performed by applying magnetic focusing fields provided by solenoids along the beam line. In this paper, the design of a microtip field emitter is introduced and characterized in electromagnetic field simulations in the gun cavity. A series of particle tracking simulations are conducted for multi-parametric optimization of the parameters of the produced quasi cw electron beams. The obtained results will be presented and discussed. In addition, measurements of the parasitic field emission (PFE) current (dark current) in the PITZ gun will be exemplarily shown to distinguish its order of magnitude from the produced beam current by the designed field emitter.

1. Introduction

Laboratory astrophysics has drawn growing interest in the astrophysics community over the last decade [1–8]. Alternatively to conventional methods of observation and numerical simulation, it is assumed to be an efficient way to improve our understanding of astrophysical processes in the environment of a scaled laboratory experiment. One interesting laboratory experiment considered at the Photo Injector Test facility at DESY in Zeuthen (PITZ) attempts to find the responsible mechanism for PeV-scale high energy cosmic-ray particles. As a promising candidate, the Bell's instability [7,8], a non-resonant instability driven by cosmic-ray current, is proposed to be the cause for those ultra-highly energetic particles by inducing turbulent amplification of the interstellar magnetic field in the upstream region of supernova remnant shocks. In order to study the Bell's instability, a laboratory experiment using the PITZ accelerator was proposed [9] based on the mechanism of electron beam driven magnetic instability growth in a matching plasma environment provided by the plasma cell of PITZ [10]. Such an experiment sets specific requirements on quality parameters of the laboratory plasma and electron beams. Preliminary analysis in [9] has shown that the electron beam parameters will be crucial for the occurrence of the Bell's instability. This includes beam duration of milliseconds (ms), average beam current of milliamperes (mA), mean beam energy of a few MeV and a properly focused beam with a transverse size matched to the aperture of the plasma cell and the plasma density. A variety of advanced beam diagnostics is thus required to validate that the experimental conditions are fulfilled.

One solution to generate such electron beams in the PITZ gun is to use field emission (FE) from a metal based on the Fowler–Nordheim (FN) theory [11]. In an RF (pulsed) regime this allows producing sub-ns electron bunches with peak currents of a few tens of mA during one period of the resonance frequency of the gun cavity (see details in Section 3). In comparison to the operation in the DC regime, the advantage of the RF

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gun performance thus remains in terms of higher beam energy [12]. However, gaps exist in between electron bunches generated from neighboring RF cycles preventing overall formation of a cw electron beam. Thus, the normal conducting 14-Cell L-band cut-disk accelerating structure downstream of the gun (booster) is used as a debunching cavity to lengthen the electron bunch within each RF period [13]. By properly tuning operation conditions of the booster a quasi cw electron beam can be formed by joining all individual bunches from neighboring RF cycles. It should be noted, that this idea could also be simply extended to similar solutions such as the use of a DC electron gun or a thermionic RF gun along with a booster cavity downstream, although technical issues may be different in each specific case. In this paper, we will focus only on the exemplary case of using an RF gun with field emission cathode for feasibility studies with available equipment of the PITZ accelerator. Note, in addition, that more specific requirements on electron beam quality parameters (such as transverse emittance and energy spread) should be determined from further astrophysical-plasma simulations by investigating possible impacts of the beam quality on the properties of the induced Bell's mode (e.g., growth rate, suppression of other instabilities).

The paper is organized as follows. In Section 2, an overview of the PITZ facility is given. The RF gun of PITZ is described. In Section 3, measurements of the parasitic field emission current (i.e., dark current) in the PITZ gun are presented. A metallic field emitter placed on the backplane of the gun cavity is specially designed. It is used to enhance the local electric field gradient at a microtip for initiating pronounced field emission (FE). The FE based electron beams are then generated according to the Fowler–Nordheim theory. Using the modified electric field maps tracking simulations of field-emitted electron bunches are performed up to the entrance of the plasma cell in Section 4. The quasi cw beams are optimized by tuning operation conditions of the booster and a set of solenoids for fulfilling the experimental conditions as stated above. A summary and an outlook are given in Section 5.

2. Facility overview and the RF gun of PITZ

The Photo Injector Test facility at DESY in Zeuthen (PITZ), was built to test, develop and experimentally optimize high brightness photoelectron sources for the operation of TESLA technology based Free Electron Lasers (FELs). The RF guns prepared at PITZ are in use at the Free electron LASer in Hamburg (FLASH) and the European X-ray Free Electron Laser (European XFEL). The PITZ LINAC consists of an L-band 1.6-Cell normal conducting (NC) RF gun, a pair of focusing solenoids, an NC 14-Cell booster cavity, and various advanced systems for electron beam diagnostics. The RF gun, the booster cavity and the plasma cell are located at 0, 2.7 and 6.0 m (starting positions w.r.t. the cathode plane) in the beam line, respectively. The interested reader is referred to [14,15] for a detailed description of the facility. Reports on plasma acceleration research activities at PITZ can be found in [16,17].

The key component of the PITZ accelerator is an RF gun [18,19], as illustrated in Fig. 1. It is composed of a 1.3 GHz copper resonator operated in π mode, coaxial RF power coupler, door-knob transition, input waveguide and supporting systems.

The PITZ gun can be operated with a high electric field gradient of about 60 MV/m on the cathode surface, resulting in a high peak RF power of about 6.5 MW in the cavity. It allows operation with long RF pulses of up to (650–1000) μs at a repetition rate of 10 Hz. This defines a high average RF power of more than 50 kW, dissipated in a rather short cavity length of about 20 cm. The gun has, meanwhile, shown a good RF amplitude stability of about 2e−4 and a phase stability of about 0.06 deg during its operation [20].

3. Field emitted electron beam in the gun

Field emission (FE) from metals refers to quantum mechanical tunneling of conduction band electrons through the potential barrier at the surface of the metal. The FE-based electrons can be extracted

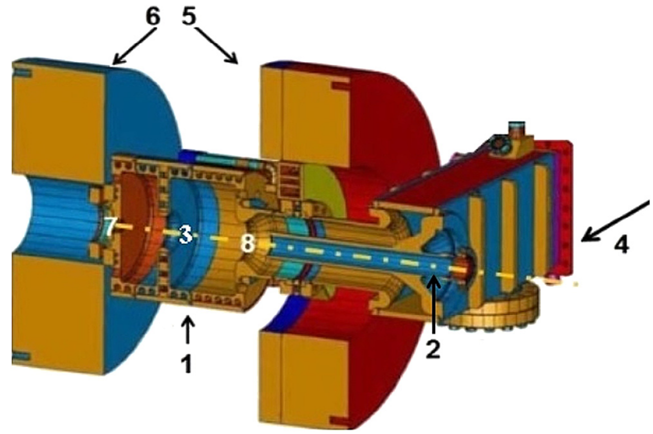

Fig. 1. Cut-view sketch of the PITZ RF gun and its surrounding solenoids: 1—gun cavity, 2—door-knob transition, 3—cavity axis, 4—RF feeding direction, 5—main solenoid, 6—bucking solenoid, 7—cathode and 8—end of coaxial line.

when a GV/m-scale electric field gradient is locally formed at the field emitter (i.e., a needle cathode). This process is described by the Fowler–Nordheim (FN) equation [11]. In an RF regime, the emission current is expressed as

$$I = \frac{5.7\times10^{-12}\times10^{4.52\phi^{-0.5}}\times A_e {E_s}^{2.5}}{\phi^{1.75}}\times\exp(-\frac{6.53\times10^9\times\phi^{1.5}}{E_s}), \quad (1)$$

and the RMS emission duration is derived as

$$\sigma_t \approx \frac{1}{\omega}\sqrt{\frac{\beta E_0}{6.53\times10^9\times\phi^{1.5}}}. \quad (2)$$

The term I represents the peak FE current while E_s characterizes the enhanced local electric field with $E_s = \beta E = \beta E_0 \cos\omega t$, where E stands for the macroscopic surface field oscillating with an angular frequency of ω and E_0 denotes the maximum amplitude of the field. The symbols ϕ and A_e denote work function of the field emitter material and the effective emitting area, respectively. The field enhancement factor β is defined here as the ratio of the enhanced local electric field E_s to the original applied electric field E. The RMS emission duration per RF cycle σ_t is a function of emitter material work function, field enhancement factor and maximum amplitude (E_0) of the RF electric field. Note in addition that all parameters are expressed in SI units.

Parasitic field emission (PFE) usually exists already in high field regions of an accelerating structure [21,22]. This can for example refer to field emitted electrons born in the cathode area of the gun cavity, some of which may be captured by the accelerating fields and further transported downstream in the accelerator chain. Due to its complex nature of dynamics, the resulting PFE electron current, namely, dark current, is undesirable for accelerator operations. But, the dark current is usually several orders of magnitude lower compared to a controllable field emission beam current produced from a specially designed field emitter (see next subsections for details). In the following, measurements of the dark current in the PITZ gun are shown first.

3.1. Measurements of dark current in the PITZ gun

The dark current in the gun cavity is measured with a Faraday cup located at about 1.4 m downstream from the cathode position. Characterization of the dark current is performed by varying the strength of the focusing magnetic field provided by the main solenoid in the gun section (see Fig. 1).

Fig. 2 shows the measured dark current in the gun cavity as a function of the main solenoid current when a flat cathode [14] is inserted in the cavity backplane. This is measured for an RF power of about 6.4 MW in the gun with a long RF macropulse of 650 μs. As