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Design of a plasma discharge circuit for particle wakefield acceleration

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ABSTRACT

Plasma wakefield acceleration is the most promising acceleration technique known nowadays, able to provide very high accelerating fields (10–100 GV m^{-1}), enabling acceleration of electrons to GeV energy in few centimetres. However, the quality of the electron bunches accelerated with this technique is still not comparable with that of conventional accelerators; radiofrequency-based accelerators, in fact, are limited in the accelerating field (10–100 MV m^{-1}) requiring therefore kilometric distances to reach the GeV energies, but can provide very bright electron bunches. Combining high brightness electron bunches from conventional accelerators and high accelerating fields reachable with plasmas could be a good compromise allowing to further accelerate high brightness electron bunches coming from LINAC while preserving electron beam quality. Following the idea of plasma wave resonant excitation driven by a train of short bunches, we have started to study the requirements in terms of plasma for SPARC-LAB [1,2]. In particular, here we focus on the ionization process; we show a simplified model to study the evolution of plasma induced by discharge, very useful to design the discharge circuit able to fully ionize the gas and bring the plasma at the needed temperature and density.

1. Introduction

Particle wakefield acceleration (PWFA) is a technique developed to combine the high brightness electron bunches from conventional accelerators and the high accelerating field that can be reached from plasmas. The needs of a PWFA are two: a train of high quality electron bunches and a plasma. The plasma can be generated either by injecting high energy electrons in a gas or by producing a discharge in a gas, while the train of high quality electron bunches is generated by conventional accelerators. In particular, in our experiment, we will use a train of electron bunches coming from the SPARC linac [3,4]; the train of electron bunches are produced by the so-called Laser Comb Technique [5] proposed by the SPARC team few years ago and which has been recently tested with the SPARC photoinjector without the plasma [6,7].

The scheme of principle of the PWFA is shown in Fig. 1.

The train of electron bunches (propagating toward the right hand side inside the plasma) is composed – in the specific case of Fig. 1 – by three driver bunches, which create the plasma wakefield, and one witness bunch, which will surf on the wakefield prepared by the driver bunches and which will be further accelerated.

With such a train of N_T bunches a resonant excitation of plasma waves can be performed with the following scaling law [8–10]:

$$E_{acc}\ [\mathrm{MV/m}] = \left(244\,\frac{N_b}{2\times 10^{10}}\right)\left(\frac{600}{\sigma_z\ [\mu\mathrm{m}]}\right)^2 N_T^2.$$

So, for example, with a train of 4 bunches with 16 pC/bunch separated by one plasma wavelength (160 μm), propagating in a plasma of density 3×10^{22} particles/m^3 can generate an accelerating field in excess of 3 GV/m.

In this paper we focus on the production of the plasma for the accelerating technique described above. In particular, we will concentrate on the plasma discharge (mainly because the SPARC electron bunches are not sufficiently energetic to ionize the gas) and we will describe a simplified model that we have used to design the discharge circuit that we will use for our experiment. Because the model does not take into account some of the physical

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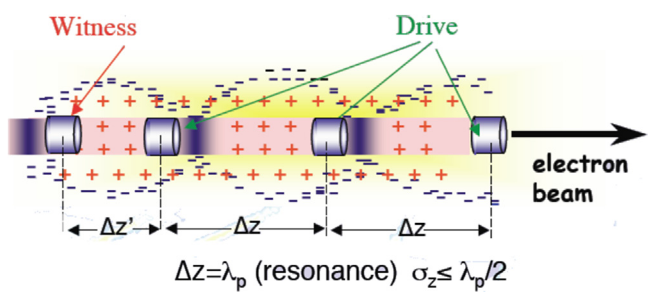

Fig. 1. Particle wakefield acceleration scheme.

mechanisms that exist during discharge (like heat transport and power losses), what we aim to find are the order of magnitudes of the discharge properties (like discharge duration, raising time and so on) and of the discharge circuit (maximum voltage and current, resistance, capacitor and so on).

2. Equations describing the gas ionization

In this section, we will list the plasma formulas that we have used to describe the ionization process. The most important formula that we use is Saha equations, which describe the degree of ionization of the plasma as a function of the temperature, density, and ionization energies of the atoms. However, this formula is only valid at thermal equilibrium and for weakly ionized plasmas (such that the Debay length is large and continuum lowering is negligible), but is sufficiently accurate for our purpose. For a gas composed of a single atomic species, the Saha equation is written as [11]

$$\frac{n_i}{n_n} = 2.4 \times 10^{21} \frac{T^{3/2}}{n_i} e^{-U_i/kT}$$

where n_i/n_n is the ionization fraction, n_i and n_n are the ionized and neutral particle densities respectively, T is the plasma temperature in K, U_i is the ionization potential and k is the Boltzmann constant. This formula is telling us that in order to bring the matter to the state of plasma, we need to increase its temperature until the density of ionized particle is much higher than the density of the neutrals. In the case of hydrogen ($U_i \approx 13.6$ eV), the temperature that ensures that the gas is in the state of plasma is about 2 eV (20 000 K) [11].

This discussion is useful to understand that in fact to study the ionization process we have to study the temperature growth as a function of the time.

The first formula needed to describe the temperature growth is the resistance of the plasma column [12]:

$$R_p = \rho_e \frac{L_{cap}}{S_{cap}} = B_{res} Z \frac{\ln(\Lambda)}{T_e^{3/2}} \frac{L_{cap}}{S_{cap}}$$

where ρ_e is the plasma resistivity which describes the evolution of the plasma resistivity due to the collisions between electrons and ions, Z is the ionization degree and $\ln(\Lambda)$ is the Coulomb logarithm (which is 10 for most of the laboratory plasmas). L_{cap} and S_{cap} are the length and the cross-sectional area of the plasma holder, usually called capillary.

Next equation is the thermal capacity at constant volume:

$$C_V = \frac{3}{2} k n_a V = \frac{3}{2} \frac{PV}{T_{iniz}}$$

where k is the Boltzmann constant, P is the pressure, V is the volume, T_{iniz} is the initial temperature (room temperature ≈ 300 K) and n_a is the atom density, which is related to the electron n_e, ion n_i and neutral n_n densities as follows: $n_i = Z n_a$, $n_e = n_i$ and $n_n = n_a - n_e$.

The temperature growth can then be written (neglecting the thermal power transferred to the capillary tube and the one emitted from the gas by radiation) as

$$\frac{dT}{dt} = \frac{1}{C_V} R_p I_p^2 = \frac{1}{C_V} B_{res} Z \frac{\ln(\Lambda)}{T_e^{3/2}} \frac{L_{cap}}{\pi r_{cap}^2} I_p^2$$

where I_p is the current used to trigger the discharge and Z is the ionization degree.

This equation can be easily integrated only assuming that the ionization degree and the discharge current are constant; under these strong hypothesis the solution is

$$T[t] = \left[T_{iniz}^{5/2} + \frac{5}{2} B_{res} Z \frac{\ln(\Lambda)}{C_V} \frac{L_{cap}}{\pi r_{cap}^2} I_p^2 t \right]^{2/5}.$$

Fig. 2 shows the temperature growth obtained using a discharge peak current $I_p = 20$ A and a ionization degree $Z = 0.5$.

However, in reality both the discharge current and the ionization degree are time dependent and this has to be taken into account to properly design the discharge circuit.

3. Ionization degree and discharge current

The result given before is not reliable because in reality ionization degree and discharge current are not constant and also they depend on the gas used.

Let us consider as gas to ionize the hydrogen, which has a ionization potential $U_i \approx 13.6$ eV. The ionization degree Z for the hydrogen can be derived from the Saha equation [11]:

$$\frac{Z^2}{1 - Z^2} \approx 2.4 \times 10^{15} \frac{T^{3/2}}{n_i} e^{-U_i/kT}.$$

If now we use this equation inside the Spitzer equation of plasma resistivity, what happens is that the initial plasma resistivity is 0 – as shown in Fig. 3 – which is not physical.

In fact, a non-ionized gas is not a conductive medium but it is an insulator, which means that the initial plasma resistivity should be infinity and not zero. This behavior is due to the fact that the Spitzer formula for plasma resistivity is only valid for weakly/fully ionized gas and not for non-ionized gas. Therefore, we need to write a Spitzer-like formula for the plasma resistivity which is valid at the really beginning of the discharge, when the gas is non-ionized. To do so, we use the same approach used by Spitzer to write the plasma resistivity for a weakly ionized gas. Spitzer, in fact, estimates the plasma resistivity by calculating the rate of collisions between ions and electrons. For a gas in its neutral conditions, the collisions happen only between atoms and electrons. In gases, in fact, there is always a very low percentage of free electrons, coming from natural reasons like heat, light and so on.

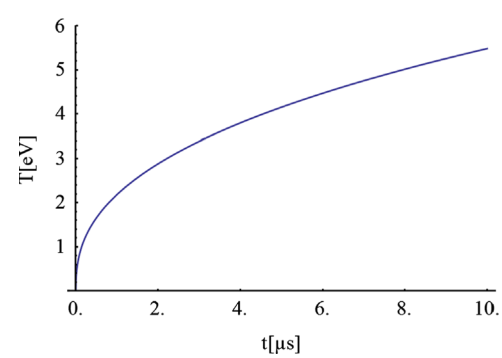

Fig. 2. Temperature growth as function of the time for $I_p = 20$ A, $Z = 0.5$.