INVESTIGATIONS OF PLASMA WAKEFIELDS IN NSC KIPT

(TO MEMORY OF A.K.BEREZIN, OVERVIEW)

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Along with reviewing of the world wide investigations of wakefields, excited in plasma by a short electron bunch or a train of bunches and by laser beat-wave or a short laser pulse, the theoretical and experimental research activity in National Science Center "Kharkov Institute of Physics and Technology" (NSC KIPT) with the aim of plasma wakefields excitation by a train of relativistic electron bunches, produced by resonant lin acs, are represented. The considerable attention is devoted to the wakefields investigation in the experimental department, headed by A.K.Berezin. Plasma wakefields are reviewed as a tool for elaboration of accelerators of new generation, plasma lens for relativistic electron beam focusing, and for development of new principles of HF-generators construction The researching works performed in NSC KIPT and planned in the future are discussed. The state of art and perspectives of theoretical and experimental investigations are considered. The recent achievements in the laboratories of the world are represented.

1. Introduction

The next further step in development of advanced methods of charge particle acceleration, particle focusing, and high-power electromagnetic generation became real due to the possibility of high intensity wakefields obtaining in plasma. There are two ways of plasma wakefields excitation (PWF) - by means of high power (~10^{15}W range) very short (~10^{-15}sec range) laser pulse, propagating in plasma or by a short bunch with large number electrons (10^{11}-10^{12}cm^{-3}) injection into plasma. In both cases the main goal is the displacement of electrons relatively to ions in plasma at a distance of plasma wave length to generate electric fields of high intensity due to large number of separated charges in plasma of high density. The maximum electric field arising during whole separation of electrons and ions in plasma of density n_p is equal to the nonrelativistic wavebreaking field value $E=mc\omega_p/e$ or $E_{max}(V/cm)=0.97(n_p(cm^{-3}))^{1/2}$ and firstly has been considered in proposal [1] to use space charge fields for charged particles acceleration in plasma and in noncompensated beams. This value is even higher $(\sim(\gamma_p)^{1/2}$, γ_p is relativistic factor) for relativistic plasma electrons [2] and due to nonstationarity of excitation [3]. Moreover for the special case of electron beam density $n_b=n_p/2$ theoretical investigations [4] have shown the E_{max} growing with relativistic factor γ_b of bunch electrons. The basic proposals [5,6] to excite wakefields in plasma by laser or electron beam promote the world-wide investigations of advanced methods of particle acceleration and elaboration of plasma-based accelerators of new generation with very high accelerating gradient. In dependence on laser or beam-based method of excitation the values of achieved fields are $E_L=0.5\cdot(eE_o/mc\omega_o)^2E_{max}$ for laser (E_o , ω_o are the amplitude and frequency of laser radiation field, correspondingly) and $E_b=(n_b/n_p)E_m$ for electron beam. Due to impressive progress in laser technology (T^3 laser) [7] and development of large charge bunch producing [8] it became possible to achieve the essential part of E_{max} (e.g. E_{max}=100 GeV/m for $n_p=10^{16}$ cm^{-3}) namely about several tens of GeV/m for laser method and about GeV/m for beam method. There are several reviews [9-13] of advanced accelerators concept based on PWF. The main goal of present overview is to cover along with recent progress in plasma-based accelerators and plasma lens, the previous old theoretical and experimental investigations of PWF excitation by a train of electron bunches that have been carried out in Kharkov Institute of Physics and Technology and to review the role of PWF in development of advanced high-power generators and amplifiers of electromagnetic radiation.

2. Electron Beam-Based PWF Excitation

2.1 The Initial Stage of Investigations of PWF Excitation

The first experiments on PWF excitation by a train of short bunches of relativistic electrons have been performed in KIPT by A.K. Berezin and his co-workers under guidance of Ya.B.Fainberg [14,15], when they started to use the beam from RF resonant electron accelerators. Initially the experimental results were interpreted as a deep-modulated relativistic electron-beam interaction with plasma. Later in [16,17] the PWF paradigm was used for the explanation of high intensity electric fields excitation and particles acceleration observation in these experiments. For PWF excitation a train of electron bunches, produced by a linear resonant electron accelerator, was used with energies 2 MeV, 14 MeV, and 20 MeV and pulsed beam current 1A (6 10^3 bunches, charge of each bunch 0.32 nC, size σ_z =1.7 cm (longitudinal) σ_r=1.0 cm (transversal)). Plasma of density 10^{11} cm^{-3} and length 1 m was produced by a coaxial plasma gun. With 2 MeV beam the coherent summation of PWF was observed. The first part of the train (4 10^3 bunches) was loosing its energy. During this time electric field intensity was linearly increasing. The further part of the train was accelerated along with PWF decreasing. The time-averaged energy spectrum represents both the maximum displacement to smaller energies and the tail of electrons accelerated. Judging by the energy gain by the electrons from spectrum tail the value of excited PWF were evaluated. It was equal to 0.2 MeV/m. The theory and simulation of PWF excitation by a train of bunches were elaborated [16-19] to evaluate the saturation amplitude and needed number of bunches. Up to now as for the number of coherent bunches the contradiction exists between theory and experiment, which may be explained by insufficient plasma density homogeneity in experiments comparatively to the model..

For electron energy 20 MeV and plasma density 10^{16} cm^{-3} the record value of electric field intensity of 400 kV/cm (energy gain 4MV at 10 cm) were obtained [16]. However in this case $\omega_p >> \omega_0$ and process should be described by modulated beam interaction with plasma, but not by PWF excitation. In particular PWF phase velocity is lowering by real part of amplification coefficient, that is not suited for acceleration of ultrarelativistic particles.

It should be noted that the theoretical investigation [20] of plasma waves excitation by a modulated beam like a train of bunches from resonant accelerators has shown that both PWF paradigm and beam-plasma interaction paradigm give the same results. It concerns electric field amplitude and phase velocity values.

The most impressive and precision experiments were performed in ANL [21]. Electron bunch of energy 21 MeV, charge 4nC and sizes σ_z=2.1 mm, σ_r=1.4 mm was injected into plasma of density (0.4-7) 10^{13} cm^{-3} and length 33 cm. For PWF measurements the bunch-witness of a small density and energy of 15 MeV was splited off from driving bunch at carbon target. By changing of its trajectory length by means of moveable magnets the time delay between driving and witness bunches input in plasma was varied from 0.2 ns to 1 ns. The measurements showed that PWF of intensity 5.3 MV/m was excited. The theory and simulation for this value gave 6 MV/m and 7 MV/m, correspondingly.

Similarly to KIPT experiment the PWF excitation by a train of 6 bunches of energy 250 MeV and 500 MeV and total charge 5-10 nC was made by KEK group [22]. Pulsed beam of duration 4 ps preliminary compressed to 2 ps was cut by RF-cavity at frequency $\omega/2\pi$=2856 MHz on several bunches with sizes σ_z=3 mm, σ_r=1-1.5 mm. Bunches were injected into plasma of density 4-9 $10^{11} cm^{-3}$ and length 20 cm so that plasma frequency is equal or multiple to sequence frequency ($\omega_p = n\omega_0$). For bunches of smaller density and energy (σ_r=1.5 mm, W=250 MeV) at plasma density n_p=4 10^{11} cm^{-3} (m=2) the energy losses of 4th and 5th bunches were 3 MeV and 4 MeV, correspondingly. In the case of dense bunches and higher energy (σ_r=1 mm, W=547 MeV) the maximum energy loss of the most intensive bunch was 12 MeV at plasma density n_p=9 10^{11} cm^{-3} (m=3). It corresponds to the electric field intensity 60 MV/m at a distance 0.2 m.

The main parameters of these three experiments are represented in Table 1.

Table 1.

First-generation beam based PWA experiments

Parameters	KIPT	ANL	KEK
Energy, MeV	2	21	250 (500)
Bunch duration, ps	57	7	10
Bunch sizes, mm			
longitudinal σ_z	17	2.1	3
diameter σ_r	10	2.8	2—3
Charge of bunch, nC	0.32	4	5—10
Number of electrons in bunch	$2\cdot10^9$	$2.5\cdot10^{10}$	3—$6\cdot10^{10}$
Number of bunches	$6\cdot10^3$	1	6
Frequency of bunches sequence, MHz	2805	—	2856
Plasma density, cm^{-3}	10^{11}	4-$7\cdot10^{12}$	$4\cdot10^{11}$
Plasma length, cm	100	33	20
Intensity of excited electric field, MV/m	0.2	5.3	60

2.2 Planned Experiments on Beam-Based PWF Excitation

It is very important not only to excite PWF of high intensity, but to provide high energy gain by particles accelerated. From this point of view the first and the best experimental results of PWF-based acceleration schemes are reviewed in [13]. In order to obtain high energy gain in the beam PWF acceleration, it is essential to overcome the transformer limit. Three methods are proposed. The first one is the use of driving beam consisting of multiple bunches. Experiments by this method are planned at KIPT [9] and INP [23-25]. The second one is the use of a single properly shaped driving beam. A triangular-shaped beam which has a linear rise over a length $L_b = L\lambda_p$ followed by a rapid termination gives the transformer ratio πN [24]. This experiment is planned at SLAC [25]. The third one is to go to non-linear regime. If the beam density n_b exceeds the plasma density n_p , the beam blows out all the plasma electrons and a nonlinear wave with large amplitude is caused [26]. The experiments are planned at ANL [8]. High-current high-density beams are essential as drive beams in these experiments. The three experiments will use such good beams in order to attain 0.1-1 GeV/m acceleration gradient.

At ANL it is planned to increase the beam current 75 times (charge of beams 100 nC, pulse duration 5 ps), and energy to 150 MeV [8]. At plasma density 2 10^{14} the expected amplitude of wakefield will exceed 1 GV/m. Besides the plasma lens with underdense plasma ($n_b > n_p$) became possible to realize.

In KEK group [27] it was supposed to increase plasma density to 10^{14} cm^{-3} and to increase transformer coefficient by varying of envelope of train of bunches. Similarly to ANL experiment at twin accelerator in Tokyo University driving bunch (28MeV 500pC) and witness-bunch (18 MeV, 50 pC) will be used to investigate PWF excitation [28]. Now in KEK group the main efforts are concentrated on laser-based PWF, because of higher electric field intensity being achieved in this case.

In KIPT [9] the experiments with electrons energy 300 MeV and 2 GeV are planned to investigate the PWF-excitation dependence on relativistic factor γ_b of the beam. Another experiment is devoted to observe focusing both by PWF an selfmagnetic field interesting for collider problems in high energy physics. Several bunches of pencil type (σ_z=1 cm, σ_r=0.14 cm) of 15 MeV energy and 12 A current is intended to use for the investigation of PWF focusing processes [29]. For PWF topography investigation the probing beam of low energy (10 keV) and small current (10-50 mA) will be injected perpendicularly to the motion direction of the driving bunches [30].

In ErPI [31] the experiments are planned on injection of a linear RF-accelerator electron beam of current 1-1.5 A and energy 30 MeV (50 MeV at a half of current) into plasma of density 10^9-10^{13} cm^{-3} of length 35 cm and diameter 10 cm. For PWF measurement it is attend to inject additional electron bunch of energy 15 MeV with regulated time delay.

Among the new projects the proposal of INP [23] to use the electron beam of existing booster accelerator BEP takes the most serious attention. The high energy (800 MeV) and significant current (1-2 A) allows to obtain short dense bunches of relativistic particles. The formation of short bunches are performed by the following scheme. RF-modulator turns the long bunch (macrobunch) perpendicularly to the direction of motion. By means of so called cutter with transparent slots macrobunch is devided on 6 bunches. After returning to the initial orientation by using RF-compensator they injected into the plasma. Theoretical analysis and simulation have been shown that in plasma of density 10^{15} cm^{-3} such train of bunches excites total PWF $E_{max} \geq 1$ GeV/m.

At present now the experiment the experimental layout is being revised [32] to make the scheme less expensive. Initially the booster accelerator BEP was supposed to be used as the driving beam source. Now upon leaving the BEP, the driving electron beam will pass almost full circumference of VEPP2-M storage ring (about 22.5 meters) and enter PWF accelerator channel placed in separate shielded hall.

The first stage of the experiment will be performed without beam density modulation, and with the presently available beam parameters: energy about 0.5 GeV, number of particles per macro-bunch $2\cdot10^{11}$, longitudinal dimension $\sigma_z \sim 15$ cm (peak current about 60 A). The PWF accelerator channel will include the 10 m length drift tube with a set of quadruples (required to transport the bunch properly), the 1m long plasma column, and the magnetic energy analyzer at the end.

At the second stage of the experiment, the following significant improvements of the driver parameters are going to be made: the number of particles per macro-bunch will be increased up to $3\cdot10^{11}$; longitudinal dimension will be compressed to the value $\sigma_z \sim 2$—2.5 cm; beam density modulation system (buncher) will be installed.

Transverse large amplitude electric field of PWF is suitable for relativistic particles focusing. In recent proposed experiment [33,34] known as E-157, the30 GeV electron beam of the Stanford Linear Accelerator Center (SLAC) Final Focus Test Beam (FFTB) is sent in a plasma with an electron density 2-4 10^{14} cm^{-3} range. Numerical simulation show that the electron bunch excites a wake (longitudinal plasma wave) with a maximum amplitude of 1 GV/m, making it possible for the first time to accelerate electrons by 1 GeV over 1 meter. The electrons of the bulk of the electron beam drive the wake and loose about 200 MeV/m, while the trailing electrons of the same bunch experience the acceleration and gain about 1 GeV/m

3. Laser-Based PWF Excitation

Follow to [13] the sequential successes in laser-based scheme development are represented below. There are three schemes of PWF excitation by means of laser radiation. In the basic proposal [5] two laser-based schemes were supposed to use, which are now called beat wave acceleration (BWA), using beating of two laser rays to excite plasma wave and laser wakefield acceleration (LWA) with PWF excitation by a short power laser pulse. The third scheme - the self-modulated wave field acceleration (sm-LWA) - became real due to high power of recent lasers. Using selfmodulation mechanism and taking measures for overcoming of diffraction limit (plasma channel, relativistic focusing) this concept seems to be the most promising.

Because of absence of high power lasers available for LWA in 80’s the experiments were firstly performed with BWA [35-38]. The main problem in BWA is the maintaining a strong resonance between PWF frequency and difference frequency of lasers rays and hence, very high accuracy of plasma density homogeneity. The accelerating field was observed at a distance of only several mm. The success in homogeneous plasma density obtaining is achieved in Rotherford Lab [36] and Ecole Politechnique [37]. In experiment at ILE [38] PWF acceleration of 10 MeV was excited at length 3-7 mm. A few good experiments on BWA were represented in [39-41].

The best results on BWA investigations is obtained by UCLA [35], where PWF of 2.8 GeV/m at length 1 cm was excited and around 10^4 electrons were accelerated to energy 28 MeV.

The LWA concept does not require the high extent of plasma homogeneity and is free of dangerous instabilities with inverse increment less than laser pulse duration. Invention of the chirped-pulse amplifier (CPA) [42] has enabled LWA investigators to use a high-power laser with pulse duration close to period of high density plasma wave. The first experiment of the LWA was made by KEK group, using CPA laser at ILE [41]. In [43] the acceleration of 10^2 particles to energy 12 MeV at distance 10 mm were reported. Recently a wakefield of the order of 10 GeV/m in a plasma was directly observed by the use of a compact terawatt laser system so called T^3 lasers [7].

The best results on LWA have obtained by KEK/JAERI/U.Tokyo group [45], using a 1.8 Tw, 90 fs laser pulse synchronized with 17 MeV RF linac electron beam injector at the repetition rate of 10 Hz. They observed high energy electrons accelerated over 100 MeV up to 300 MeV by the wakefield of ~15 GeV/m excited over 2 cm long underdense plasma, created in 20 Torr He gas.

The sm-LWA being considered [46,47] as Raman scattering in power laser electromagnetic wave interaction with plasma demonstrated [43] ultrahigh gradient electron acceleration of 30 GeV/m (energy gain 18 MeV at 0.6 mm), using a multiterawatt short laser pulse. However such intense accelerating field is excited at a short length, limited by diffraction limits (Rayleigh length) dephasing of accelerated electrons or depletion of pump pulses. To overcome this drawback the development of optical guiding schemes in plasma and spatial and temporal matching technology is being performed. The sm-LWA scheme results in extremely large acceleration gradient 44 MeV at distance 0.3 mm were observed in RAL experiments [48].

The laser with power of 25 Tw in those experiment was used. The number of electrons accelerated was 10^8 and the normalized emittance was calculated as $5\pi\mu$m for electrons with energy 30 MeV. Recent report informs that a new detector has found electrons with energy up to 100 MeV.

4. Perspectives of Beam and Laser-Plasma Accelerators

The first generated investigations of PWF are the proof-of-principle experiments. At present the perspectives to evaluate the design of TeV range linear colliders based on PWF have arisen. It is now obvious that recent progress in laser technology (e.g. T^3 laser creation) allows to produce higher intensity of accelerating field in laser-based plasma accelerator comparatively to beam-based one. However from requirements of high energy physics [49] it follows that the driver should produce a high precision plasma field structure over a long distance. From this point of view, particle beams have some advantages over laser beams, because charged drivers, as well as the accelerated bunch, can be focused and directed strictly along the axis by external system of magnet lenses like in conventional linacs. Moreover it is limited neither diffraction nor dephasing. Below both schemes are reviewed.

4.1 Beam-Plasma Accelerator Project

The possible applications of advanced accelerator schemes is a large accelerator of TeV range energy. As a candidate for future TeV collider the following design is being considered in INP [32].

One of the crucial points of the collider concept is the way of driver preparation. As it was mentioned above the «transversal cutting» of the low emittance original beam (macrobunch) is proposed to use [32, 49] for preparing of micro-bunches train. The scheme of sequential (staging) acceleration looks as follows. A conventional linac produces the train of 100 macro-bunches for 100 plasma wakefield accelerator (PWFA) sections. Another accelerator produces the witness. The last macro-bunch (№ 100) passes the cutter and enters the first section. Other macro-bunches travel along the helical delay line, so that the macro-bunch № 99, after cutting, exactly replaces the previous exhausted driver in the gap between the first and the second sections, and so on [49].

Some PWFA-related parameters of the collider are summarized in Table 2.

Feasibility of the PWFA based collider crucially depends on the minimal achievable emittance. The plasma itself limits the final emittance by the small value 10^{-13} cm·rad [32]. It seems likely that the emittance will be determined (as in conventional linacs) by the witness pre-injector and alignment accuracy of sequential sections.

Table 2. Parameters of the collider.

Parameter	Value
Input:	
Length of each PWFA section	10 m
Number of PWFA sections	100
Number of electrons	
in the witness	$5\cdot10^9$
Plasma density	10^{15} cm-^{3}
Driver energy	10 GeV
Number of electrons	
in each macro-bunch	10^{11}
Length of each macro-bunch	1 cm
Number of micro-bunches	
per macro-bunch	7
Driver radius (0.8 c/ω_p)	0.14 mm
Output:	
Accelerating gradient	1 GeV/m
Final energy	1 TeV
Final energy spread	
(for matched witness)	3 %

4.2 Laser-Plasma Accelerator

One of the possible applications of considered concept to high energy accelerators is a 5 TeV linear collider design based on the LWA. It is described in Table 3 [48]. First assumed were wall-plug power, luminosity and the percentage of breamstrahlung. Because of the poor efficiency of the laser, the number of particles per bunch must be small. Their solution is small emittance, small final-focus beam size and short bunch length, all of which are on the order of pm. Each accelerator of the colliders has a laser-rf injector, a linac for pre-acceleration and 250 stages of laser wakefield accelerators. Each stage is 1m long, and has 10 GeV energy gain. The length is approximately equal to the dephasing and pump-depletion lengths. Two laser \

beams are fed to each stage, one of which creates an optical channel, and the other is guided in the channel.

Table 3.

Linear collider design based on LWA.

Collider parameters	
Energy	5 TeV (2.5 TeV×2.5 TeV)
Luminosity	10^{35} cm^{-2}sec^{-1}
Bunch length	~ 1 pm (=β^*)
Emittance	1pm (round beam)
No. of electrons per bunch	10^7
Bunch frequency	40 kHz
Disruption parameter	25
Breamstrahlung percentage	30%, δ_B =0.3
Upsilon parameter	10^3
Luminosity enhancement	3
Average beam power	0.25 MW
LWA parameters	
Plasma density	10^{17} m^{-3}
Acceleration length	1m
Energy gain per stage	10 GeV
Number of stages	500
Laser power per stage	40 kW
Laser energy per stage	1 J
Average laser power	20 MW

5. Plasma wake-field generators

Wakefield excited in plasma by an electron beam can serve as a buncher similarly to RF one. Its advantages conclude to high intensity of these fields and high frequency corresponding to the dense plasma frequency. A related beam buncher for accelerator applications was recently analyzed in [51]. In this case a laser driven PWF-oscillation is used to prebunch an electron beam prior to acceleration.

Two devices based on the PWF-modulator are represented below: high power generator of broadband radiation - PWF-helix generator [52] and narrow band amplifier - PWF-klystron [53].

5.1 Plasma Wake-Field Helix Generator

The concept of broadband generators based on nonrelativistic e-beam modulation by the wakefields excited in a plasma waveguide by this e-beam itself is considered. For nonrelativistic case the slow wave structure with a small phase velocity should be chosen. The generator proposed consists of three parts. At the first stage the tubular electron beam (11—11.5 KeV, current 2.5—3 A, pulse duration 160 μs, and diameter 2.5 cm) is produced by the magnetron gun that operates in specific conditions to obtain a high level noise. In the second part represented by the magnetized plasma wave guide (plasma density up to $1.6{\cdot}10^{11}$ cm^{-3} , magnetic field 1.5 kG) these stochastic noise oscillations are amplified due to the plasma wakefields excitation by the gun modulated e-beam. At the third stage the broadband modified helix slow wave structure (rode-ring combination) amplifies additionally and takes off the RF power 15 kW in the frequency band 300—500 MHz. The process considered is similar to the superradiation phenomenon. With no external initial signal and no feed back this device can be considered as a combined beam plasma generator-amplifier.

5.2 Plasma Wake-Field Klystron

This microwave source [53] utilizes a plasma to bunch the electron beam. The electron beam interacts with the plasma via the wakefield produced by the head of the beam. The resulting plasma oscillations bunch the beam at a frequency proportional to the plasma frequency. Thus the device can be tuned by varying the plasma density.

The theory of the device and numerical simulation were used for an electron beam of 500 keV energy, 5 kA current, 15 nsec rise time injected into a 25-cm-radius by 22.5-cm-long cylindrical cavity filled with a background plasma of density $2{\cdot}10^{10}$ cm^{-3} with a smaller coaxial channel of 2.5 cm radius containing twice that density. Both the current and energy bunching amplitudes increase nearly linearly with axial distance up to 19 cm at frequency f_b = 900 MHz. The plasma density and the chamber length are the fundamental parameters of the PWF bunching mechanism. The simulation shows the peak electric field to be about 3—4 MV/m at the beam radius. At the exit of plasma chamber the beam power modulation amplitude is near 60 %, while the current bunching is less than 30 %. In vacuum region they achieve the equal value ~ 50 %. Coupling power from the beam has been simulated by employing multiple klystron-like interaction cavities. As much as 1.1 GW of RF power has been extracted from this beam using a six-cavity configuration.

The proof-of-principle experiment consist of a Marx-type generator (operated at 100 kV), a beam forming diode utilizing an explosive-emission (velvet) cathode, a plasma chamber, and a short transport section employing solenoidal magnetic lenses to focus the electron beam from the diode to the plasma chamber. A single klystron-type cavity is placed downstream of the plasma chamber to measure beam coupling and energy extraction.

Essentially the entire beam current 250 A was transported through the plasma chamber when the plasma density exceeded $7{\cdot}10^9$ cm^{-3}. At lower values of plasma density, the transported current decreased linearly to about 75 A with no plasma. The bunching frequency measured by a collector and determined by performing a FFT on digitized expanded wave form was equal to plasma frequency $f_b = f_p$. It was changed from 0.8 GHz to 1.3 GHz by plasma density varying. The beam was strongly bunched in the plasma chamber at this frequency.

Significant cavity excitation was observed only when the plasma density was adjusted to induce beam bunching at a frequency near the cavity resonance (measured at 1.08 GHz in cold tests). The full width at half-maximum of the excitation curve corresponds to a variation of 160 MHz in beam-bunching frequency, whereas the cavity bandwidth is 2 MHz (Q = 500). Possible explanations of this behavior include a decrease in the cavity Q in the presence of the electron beam and possible feedback between the cavity and the plasma-bunching chamber. About 10 % (0.2 J) of the beam energy over the 100 nsec growth time of the cavity field was evaluated. The corresponding gap voltage is about 70 kV, and the peak RF electric field of the nose of the cavity gap is about 150 kV/cm.

The proof-of-principle experiment has demonstrated the PWF mechanism to be quite strong. The bunched beam that results from the axial modulation is well suited to RF energy production via interaction with standard microwave extraction structures. To take advantage of the wide tunability of the device, a traveling wave structure should be substituted, as it has been done in plasma wakefield helix device considered above [52].

6. References

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