RF PHOTOINJECTOR/LINAC DEVELOPMENT AND THEIR APPLICATIONS AT UCLA*

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Abstract

Various RF accelerator structures have been developed for acceleration of high brightness photoelectron beams at UCLA during the last several years. The first is a $1\frac{1}{2}$-cell injector, which produces 0–3 nC of photoelectrons per bunch at up to 4 MeV with an rf induced emittance of 1.5π mm–mrad. In order to boost the beam energy to 15–20 MeV, a plane wave transformer(PWT) linac was constructed, cold tested, and it is in commissioning phase. The injector and PWT combination has overall length of less than 1.5 meters. Another structure is a $7\frac{1}{2}$-cell 20 MeV injector at 1 nC per bunch. An experimental prototype was built, and cold tests are under way. The high brightness beams produced by these accelerators are being used for experiments on coherent sources in infrared and millimeter waves, along with plasma lens and plasma wakefield acceleration.

Introduction

There has been a number of improvements in production of high brightness photoelectron beams at UCLA and elsewhere[1,2]. These are characterized by the better stability in the rf and laser systems driving the photoinjector, new cathode materials with higher quantum efficiency, more control over the beam handling in terms of emittance compensation and bunch compression. All of these schemes are being implemented on the present beamline, installed in a shielding structure of 3 feet thick concrete enclosure against gamma and neutron radiation.

At the highest level of development is the $1\frac{1}{2}$-cell injector[3]. The beams out of this injector were measured in energy, charge, momentum spread, emittance, bunch length, and quantum efficiency of the cathode. The experimental parameters were energy per pulse, polarization, angle of incidence, and pulse length of the laser beam. On the rf side, they were the field strength at the cavity and the rf phase at which the photoelectrons are borne.

The plane wave transformer linac[4] has undergone a number of revisions from the original design and prototype. It has been found that the rf power dissipation at the cells were high enough to cause detuning of the resonance frequency after only a short period of operation. Leaving the basic parameters such as cell size and washer dimensions unchanged, a water cooling was employed for the structure to remain resonant, and to be able to tune it to the driving frequency. Preliminary measurements of the dark current indicate that the energy gain of the PWT will be about 13 MeV at the rf power input of 16 megawatts.

An extension of the photoinjector[5] has $7\frac{1}{2}$ cells, driven by a single waveguide feed, and numerical calculations show a beam energy of slightly higher than 20 MeV at 24 MW of rf power. An aluminum prototype was made based on this calculation. It consists of a number of full cells and half cells, along with various iris sizes. Individual cells and irises can be rearranged in many different ways, and their dimension may be modified by simple machining. The assembly is then clamped, not brazed, for a cold test. The model is under extensive simulation of the field structure and particle dynamics for an optimal set of beam characteristics it will produce.

The electron beam produced by any of the above, or combination thereof, will drive undulators for the generation of coherent radiation in infrared and millimeter waves. The undulators have been constructed and their parameters were measured. The results can be found elsewhere. For the study of beam–plasma interaction, a short bunch of photoelectrons will propagate through plasmas to undergo a focusing process, or to form plasma wakefields for an acceleration of the subsequent electron beam. The focusing of the electron beam by the plasma was experimentally verified[11]. A plasma source was built to study the plasma wakefield acceleration scheme.

RF and Laser Systems

A fair amount of efforts was given to the systems for the stability in terms of reproduceability in amplitude, phase, and timing[6]. The master oscillator runs at 38.08 MHz, the rf frequency of 2.856 GHz is the 75th harmonic of this. Previously, the rf frequency was generated by three stages

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of harmonic generator consisting of mixer, band pass filter, and amplifier. This resulted in side bands in the 74th and 76th harmonic only 12 dB down from the center frequency, leading to the beating between those bands. By incorporating a phase locked loop, the present rf spectrum has essentially a single frequency while all the side bands are down by at least 70 dB. The amplitude is stable within 0.1 dB mainly due to variations in room temperature. Further stabilization may be achieved by operating the system at some higher but constant temperature.

On the high power side, the klystron is pulsed at the saturated gain. Yet, the drift in line voltage of the primary power is as large as 5% in a few hours, resulting in the beam energy fluctuation of 2 to 3%. In order to stabilize the klystron cathode voltage, a voltage regulator based on phase angle control SCR was installed. It regulates the voltage at the pulse forming network by a feedback control. As a result, the present level of the beam energy fluctuation is less than 0.1%, as measured by shot-to-shot peak energy of the dark current.

The energy per pulse from the drive laser varies by as much as 20 to 30% or more. So each pulse is monitored in energy as an experimental parameter. However, the timing jitter has been reduced to about 1 ps, corresponding to the measured photoelectron beam momentum fluctuation of 0.3%, by employing a feedback stabilizer at the mode locker. The laser system is capable of delivering 400 μJ of photon energy to the cathode at the wavelength of 266 nm in pulses of 1 to 50 ps. And the rf system can supply 24 MW of power at 2.856 GHz in 3 μs pulses. The rep rate is limited to 5 Hz by the laser situation and other engineering considerations.

Accelerating Structures

The $1\frac{1}{2}$-cell photoinjector has been successfully operated in the past. Now it is under recommissioning process after a retuning and balancing. The performance of the gun is summarized in Ref[3]. The highlights are as follows.

1) The beam energy is the highest at 3.5 MeV when the photoelectrons are emitted at the rf phase of 45° and falls off to 3.0 MeV at 0° and to 2.9 MeV at 79°. This is consistent with numerical solution of equations of motion. The derated maximum energy from the design value of 4.5 MeV is caused by the imbalance of the fields in the half cell and full cell ($E_{z,full}/E_{z,half}$ = 1.8) as a result of inaccurate positioning of the cathode.

2) The rms momentum spread $\delta\gamma/\gamma$ was 0.2% at the bunch charge of less than 50 pC, increasing to about 0.4% at 100 pC. This is due to space charge forces and phase increase from the bunch lengthening.

3) With a 2 ps long laser pulse, the bunch length was measured at 12 ps FWHM by a streak camera looking at a fused silica Cherenkov radiator. A PARMELA simulation reveals bunch lengthening from the space charge forces, giving 3 ps at 50 pC and monotonically increasing to 16 ps at 1.2 nC.

4) The quantum efficiency measurements show that the 70° injection of laser beam (λ=266nm) with p-polarization gives the best efficiency of 1.3×10^{-4} for the laser energy up to 50 μJ to the copper cathode, for a bunch charge of 1.4 nC. It falls off as the bunch charge is increased, again a manifestation of space charge forces.

5) The normalized beam emittance is a linear function of the bunch charge. Experimental data from a pepper pot measurements can be represented by ϵ_n (mm-mrad) = 1.7 + 15.5 q (nC) for $0.12 \leq q/\mathrm{nC} \leq 0.44$ at 3.5 MeV

6) The rf induced emittance in πmm-mrad, which was measured by extrapolation to a zero charge, as a function of laser injection phase ranges from 1 at 20° to 10 at 45°. For a 1 nC charge, it was from 10 at 45° to 20 at 30°.

7) The normalized emittance as a function of beam energy is ϵ_n (mm-mrad) = 29 - 5.5 E (MeV) for $2.7 \leq E/\mathrm{MeV} \leq 3.8$ at constant charge and phase.

This injector will remain to be an active part of the whole system and basis for the future development. There are areas where improvements are needed, such as field balance between the cells and use of cesium telluride on cathode for about 10% of quantum efficiency. The PWT linac is to boost the beam energy after the photoinjector to about 20 MeV. The device is characterized by high shunt impedance (ZT^2/L = 40MΩ/m), compactness (L = 42cm), and insensitivity to machining errors, since off axis coupling allows localization of any error. The original design lacks active cooling of the cells, where the rf power dissipation is very high, leading to a detuning of the structure. The detuning rate was measured at –35 kHz/°C. Four water tubings running in longitudinal direction at the edge of the washers carry water at constant temperature, which is adjusted for the purpose of tuning.

The field profile as measured by bead pulling technique shows somewhat high spatial harmonic contents. For a single bunch operation, it may be tolerated. When there is more than one bunch in the same macropulse, the trailing bunches may suffer emittance degradation from this harmonics. The outcome is yet to be seen since the device is currently undergoing a commissioning process.

For the purpose of mitigating the effects of harmonics, and to lower the surface electric fields on the washers, an aluminum model was made based on revised design of washers. Cold test and computer simulation indicate that those two problems are rectified by this new design. The combination of the $1\frac{1}{2}$-cell injector and the PWT adds complexity in the rf power delivery as well as the matching of the two structures. So the $7\frac{1}{2}$-cell photoinjector under development is a potential solution. This will have on axis coupling, terminated by cathode in half cell and a full cell at the exit. Although the previous design, terminated by half cells at either end, had excellent shunt impedance and field balance, it turns out to be less realistic in that the field balance is destroyed as an opening is made for a beam exit. The present design has still high shunt impedance of ZT^2/L =45.2MΩ/m with a fill time of less than 1 μs, although the field profile is $E_z(z) = E_0 \exp\{-(z/5.8L)^2\} \cos(\pi z/L)$ where L is the half cell length of 5.25 cm.

This injector is a standing wave, π-mode running at 2.856 GHz where the driving rf power of 24 MW in 3 μs pulses is available from a SLAC XK-5 klystron, which will produce beams at 20.5 MeV. The aperture between the cells is 1.5 cm in radius to realize a mode separation of about 2 MHz from $\frac{5}{6}\pi$ to π modes. Particle simulation using the PARMELA code suggests that the beam parameters will be better than the $1\frac{1}{2}$-cell injector by a factor of 4 in beam energy, 2 in transverse emittance, and more than 10 in momentum spread.

Design efforts will be continued to achieve a set of optimal machine parameters as well as particle simulation studies and cold tests on existing model, which will be done in parallel.

Applications

As the electron beams at the energy of up to 20 MeV become available, preparations are underway for the applications of these beams for the study on generation of coherent radiation, and beam-plasma interaction for acceleration and focusing of the electron beams. The first in line is an infrared FEL[7,8] at the wavelength of 10.6 μm. It will use a hybrid undulator of 60 cm length with period of 1.5 cm and peak field of 7.3 kG on axis. The undulator has been built and the field distribution was measured by Hall probe and by using a pulsed wire technique.

The electron beam should have 17 MeV of energy, 5 mm-mrad of normalized rms emittance, and 200 A of current, which is within the capability of the PWT linac. The physics issues to be addressed are self amplified spontaneous emission (SASE), high gain regime where $P(z) = P_o \exp(z/L_g)$, startup from noise, and optical guiding.

Following the IR FEL experiment, the present plan calls for mm-wave waveguide FEL[9,10]. The first wiggler to be used has period of 8.4 cm, pulsed peak field of 5 kG, length of 1.68 m, and is a helical type. It is currently available. Depending upon the wiggler field and the beam energy, the wavelength ranges from 0.5 to 3.0 mm with output power up to 50 MW. With a short bunch ($\tau_b = 6$ ps whereas $\lambda/c = 10$ ps) achievable after a bunch compression, coherent synchrotron radiation for a pre-bunched beam will be studied along with an effect of zero slippage, SASE, and wiggler focusing.

This FEL has potential for driving the two beam accelerator for a field gradient on the order of 500 MV/m while technical aspect of output coupling and diagnosing a 100 ps long mm-wave is challenging. As for the beam-plasma interaction, plasma lens experiment was completed in an overdense plasma[11] where plasma density $n_p = 0.5 \sim 5 \times 10^{12}/\text{cm}^{-3}$ and beam density $n_b = 5 \times 10^{10}/\text{cm}^{-3}$. A 25 ps long bunch of 0.6 nC at 3.8 MeV with 2.7 mm of spot size and 5 π mm-mrad of emittance travels through plasma of 6 cm length. About 21 cm down the stream, the spot size was reduced to 0.55 mm on a phosphor screen, resulting in a reduction of transverse size by a factor of five by the plasma lens.

Plasma lens experiment will be continued, and underdense plasma lens will be tested for linear radial focusing (no spherical abberation) and temporally uniform focusing (less longitudinal abberation). Another class of beam-plasma interaction for experimental test at UCLA is the plasma wakefield acceleration[12]. The wakefields are generated by a leading bunch at relativistic energy of γmc^2 in a cold plasma. The trailing bunches can be accelerated by the wakefield with an energy of up to $2\gamma mc^2$. The requirement in bunch length is that it should be shorter than one plasma oscillation period. For a 4 ps bunch, this requires a plasma density of less than 10^{14} cm^{-3}. For a bunch charge of 1 nC and plasma length of 20 cm, numerical simulation shows that the accelerating field of 150 MeV/m with an energy gain of 15 MeV is achievable. Preparation is underway for plasma source, which has hollow LaB_6 thermionic cathode, a dc discharge, and axial magnetic field confinement.

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