MODULATION OF INTENSE BEAMS IN THE UNIVERSITY OF MARYLAND ELECTRON RING*

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Abstract

All beams are dominated by space charge forces when first created. After a beam is accelerated, space charge directly plays a less important role. However, at low energy space charge will drive changes in the beam which will become "frozen in" as the beam is accelerated, and may have adverse consequences even at high energy. In this paper, we report on the generation and evolution of modulated beams in the University of Maryland Electron Ring, a low energy (10 keV), high current (100 mA) electron recirculator for the study of beams in the extreme space charge dominated regime. Such intense, modulated beams have application to future high power FELs and novel light sources.

INTRODUCTION

All beams of interest are dominated by space charge forces when first created. These forces will govern the beam's behavior until it is accelerated to sufficiently high energy. The space charge dominated regime is of increasing importance to newer, improved accelerator designs since beams with higher current and quality will remain space charge dominated longer than beams with lower current and quality. At lower energy, space charge will cause changes in the beam phase space distribution which depend on the initial conditions of the beam [1]. This can result in beam pulse lengthening [2], increased energy spread and emittance [3], and charge density wave propagation in the beam [4]. Charge density variation along the beam is of particular importance. Such modulation may arise through unintentional fluctuation in beam current at the source, for example due to structure on the drive laser pulse. Structure of this type is often found in lasers manipulated for use with photocathodes [5]. The resulting beam modulation will evolve under space charge forces, which may convert it to energy modulation, either in whole or in part. Density modulation remaining on the beam at high energy may result in the production of coherent radiation at the modulation frequency, while energy modulation may be converted back into density modulation due to dispersion in the beam transport system [6,7]. As a result, the effects of a beam's early evolution under space charge forces at low energy must be understood to fully explain its later evolution.

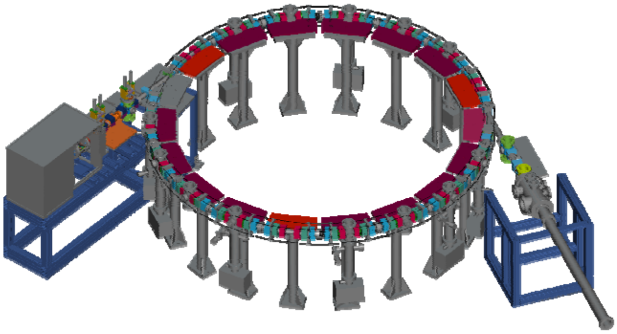

Figure 1: The University of Maryland Electron Ring [8].

Effects due to initial modulation have already been seen in high-gradient free-electron laser injectors. A previous experiment at the Deep Ultra-Violet Free-Electron Laser (DUV-FEL) facility at Brookhaven National Laboratory used a terahertz modulated titanium:sapphire laser to induce initial density modulation on the electron beam [9]. After acceleration to relativistic energy, the phase space of the electron beam was measured using a tomographic reconstruction of various phase space projections created by varying the phase or amplitude of the RF field in an accelerating structure and passing the resultant beam through a spectrometer. The measured phase space diagrams indicated that, even in this high-gradient system, the initial modulation remained on the beam, and depending on initial charge, manifested itself as either density or energy modulation, or some combination of both.

The experiment at Brookhaven found that under certain conditions, the initial density modulation could be partly washed out by space charge. Thus, not only must the (deliberate or accidental) initial density modulation be considered, but the way in which this modulation is modified by space charge forces must also be considered. Unfortunately, while the results of such interactions may be felt throughout a beam transport system, the interactions themselves are strongest at low energy. In conventional high-gradient accelerator systems, the key region in which this interaction occurs is typically in the first few RF accelerating cells near the cathode. It is difficult or impossible to directly study beam behavior in this region due to the small volume being considered, the need to maintain RF boundary conditions, and the short electron beam pulse length typically used in free-electron laser systems. To fully study modulation effects in intense beams, a dedicated machine is needed, such as the University of Maryland Electron Ring (UMER).

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UMER, a low energy (10 keV), high current (100 mA) electron recirculator (Fig. 1), has been built to investigate the generation, transport, and evolution of space charge dominated beams [10,11]. The electron beam is produced in a gridded Pierce gun [12], injected through a matching section into the ring, and extracted into a diagnostics end station equipped to measure the current, emittance, and transverse beam profile. Beam transport [13] is accomplished by use of printed circuit, air core dipoles and quadrupoles, which allow reproducible operation without hysteresis at the low field strengths needed to bend and focus the 10 keV beam in UMER. In addition to the diagnostics in the end station, UMER has beam position monitors (BPMs) every 0.64 m along its 11.6 m circumference, and at two stations in the injection and extraction sections. BPM temporal resolution is better than 2 ns, which makes them ideal for studying the evolution of the 100 ns long beam in UMER [14]. The large number of diagnostics, combined with the ability to reproducibly generate beams with various initial pulse shapes, makes UMER ideal for the study of low energy space charge effects relevant to the FEL community. In this paper, we report on the generation and evolution of modulated beams in UMER.

CONVENTIONAL OPERATION OF UMER

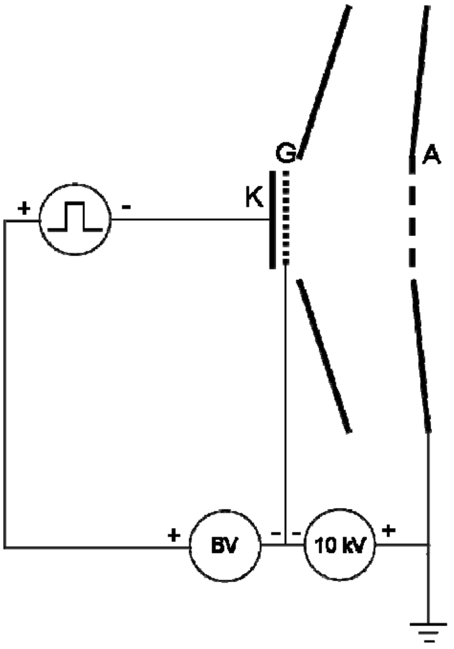

Figure 2: UMER gun configuration (simplified) [16].

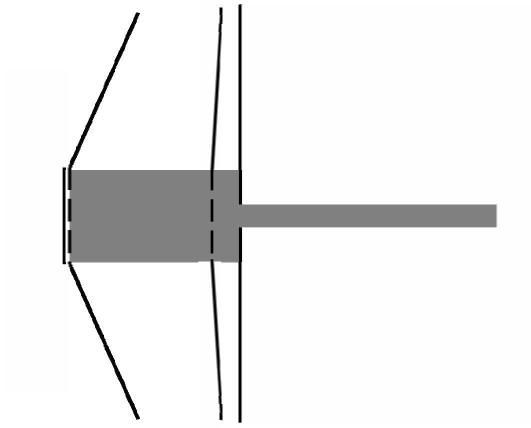

Figure 3: Beam current control by aperturing. Gun remains in stable, space charge limited mode of operation.

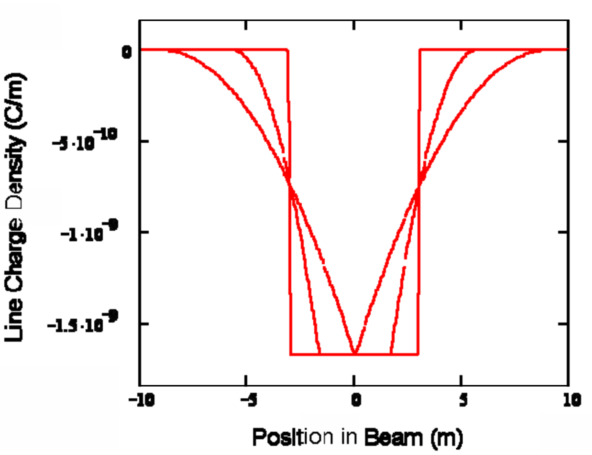

Figure 4: Expansion of rectangular, space charge dominated beam by erosion at the beam ends.

Electrons are produced in UMER from an Eimac Y-646B gridded thermionic cathode in a Pierce-geometry gun [15]. Emission from the cathode is normally suppressed by a bias voltage (BV) of approximately 40 V applied between the grid and cathode (Fig. 2). To produce beam, a cathode pulser voltage of approximately 60 V is applied directly to the cathode, allowing electrons to overcome the potential of the grid and escape into the grid-anode region, where they are accelerated out of the gun by the 10 kV accelerating potential. Current is normally adjusted by aperturing the beam exiting the electron gun (Fig. 3). Because the gun normally operates in space charge limited mode, fluctuations in emission due to nonideal cathode pulser shape are suppressed, producing a rectangular beam profile. This beam evolves under space charge forces by erosion at the beam ends (Fig. 4). The characteristic speed for this erosion is the "sound speed"

$$c_0 = \sqrt{\frac{qg\lambda_0}{4\pi\varepsilon_0 m\gamma^5}}, \qquad (1)$$

where q is the fundamental charge, λ_0 is the initial line charge density in the beam, ε_0 is the permittivity of free space, m is the mass of the electron, γ is the relativistic factor and g is a geometry factor depending on the beam radius and the beam pipe radius [2,16,17]. This is the speed at which current density disturbances will propagate in a space charge dominated beam.

PHOTOMODULATION

The thermionic cathode used in UMER has also been shown to be an effective photoemitter [18,19]. When the gun is operated in space charge limited mode, the extra electrons produced at the cathode due to illumination with laser light do not escape because of the presence of a virtual cathode in the gun. When the cathode temperature is sufficiently reduced, the current in the main beam pulse will no longer be limited by space charge in the gun, but rather by the Richardson-Dushman law. In this mode, excess electrons produced at the cathode due to photoemission will be able to escape the gun. If the laser pulse is short compared to the overall length of the main beam, the result will be a perturbation applied to the beam current. These perturbations will create a forward-traveling "fast wave" and a backward-traveling "slow wave," each traveling at the sound speed of Eq. (1) in the beam frame (Fig. 5) [4]. As beam energy is increased, the wave speed decreases. As a result, the presence of distinct, observable fast and slow waves in a beam will depend on how quickly the beam has been accelerated. However, the fast and slow waves are a manifestation of the energy modulation of particles in the beam, which arises due to the space charge force associated with the increased charge density in the perturbation [20]. Even if the fast and slow waves are not observed to separate, this energy modulation will be present, and may have adverse consequences in beam transport systems such as those used with free-electron lasers.

Fig. 5 shows the effects of a single initial density perturbation. Generally, accidental or deliberate density modulation of beams involves a more complicated pulse structure. To produce more realistic modulated beam shapes, an apparatus was developed using a laser and a system of beam splitters and delay lines to enable the production of a train of optical pulses, whose spacing, relative amplitude, and location in the main beam could be controlled. This apparatus is discussed in more detail in reference [21]. Because the dispenser cathode used in UMER is a prompt photoemitter, the photoelectron current will have the same shape as the incident laser pulse train. As a result, complicated electron beam pulse shapes can be created in a well-controlled, reproducible fashion (Fig. 6). In principle, this technique can be extended to produce arbitrarily-complicated pulse shapes by increasing the number of beam splitters and delay lines in the optical modulation system, and therefore increasing the number of laser pulses available to be directed onto the cathode. To take full advantage of this technique, dispenser photocathodes are needed that can operate over a wide range of temperatures without loss of quantum efficiency. Research is currently underway at the University of Maryland to optimize the performance of dispenser photocathodes [22-24].

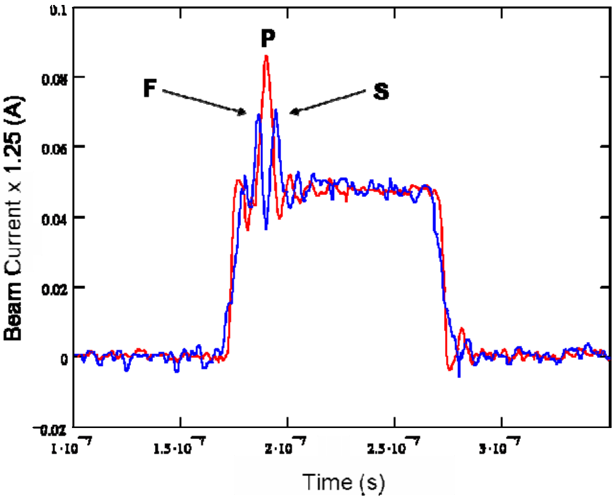

Figure 5: Production of fast wave (F) and slow wave (S) from initial perturbation (P) in 38 mA beam generated by thermionic emission in UMER. Upstream current trace is red, downstream current trace is blue. Sound speed calculated from separation of fast, slow waves is (1.60 ±0.14) Mm/s.

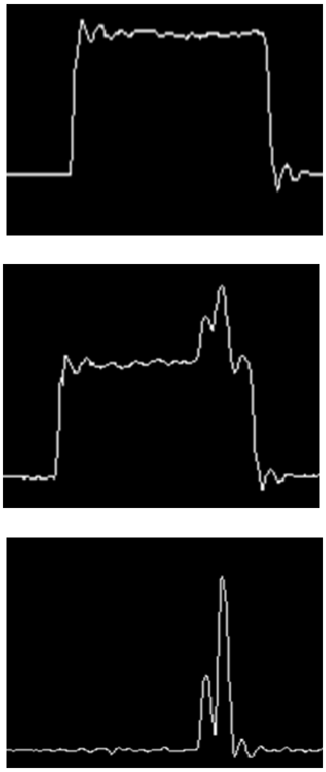

Figure 6 : Photomodulation. (Top) Operation of UMER gun with cathode illuminated by laser pulse train but operating at high temperature; gun operation is space charge limited, and no modulation is present. (Center) Operation at reduced cathode temperature, showing hybrid thermionic emission (flat top) and photomodulation. (Bottom) Operation at highly reduced cathode temperature, showing negligible thermionic emission.

TRIODE EFFECTS

The configuration of the UMER gun is essentially that of a planar triode [25]. If the bias voltage is increased to reduce the current in the gun, it will no longer be operating in space charge limited mode, but rather in triode amplification mode. Under this condition, any ringing or droop present on the cathode pulser voltage will be amplified, producing a modulated beam current. This is observed in UMER. If the modulated beam is allowed to propagate through the UMER transport system, the modulation is seen to disappear, reappear, and then begin to disappear again (Fig. 7). This is due to the initial modulation launching a fast wave and a slow wave, which interfere with each other as they propagate along the electron beam. Based on the distance from the cathode to the location of minimum observed modulation, the speed of the fast and slow waves can be calculated, and is found to be consistent with the theoretical sound speed in the beam [16]. Such effects must be considered in proposed free-electron laser systems utilizing triode-type gridded guns [26].

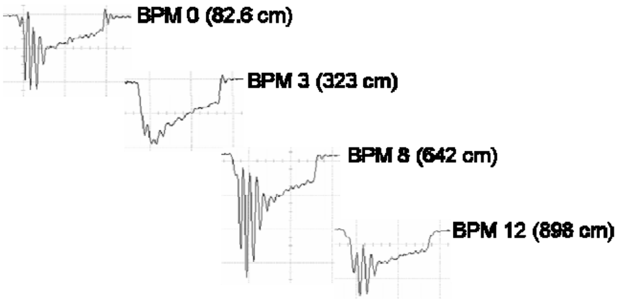

Figure 7: Evolution of sinusoidal modulation in UMER.

CONCLUSIONS

Free-electron lasers show great promise for research, industrial, medical, and national defense applications [27]. Future machines will require higher current and better quality, which will increase the importance of space charge effects, especially the space charge driven evolution of unintentional beam modulation at low energy as soon as the beam is formed. The results of this evolution will be carried with the beam, and may have an influence on machine performance even at high energy when the beam is no longer dominated by space charge forces. Research is currently ongoing at the University of Maryland Electron Ring to study the generation and evolution of beams in the extreme space charge dominated regime. Areas of active research include longitudinal expansion of beams, dispenser photocathodes, photomodulation of thermionic beams, and triode effects in gridded guns.

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