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1st+2nd HARMONIC PHOTOCATHODE BIMODAL GUN R&D*

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Abstract

A novel Bimodal Electron Gun is designed to apply microwaves at two harmonically-related frequency in a 0.6 cell RF gun to increase the RF breakdown threshold and enhance the beam quality. This stratagem is intended to allow the RF gun structure to support a high acceleration gradient as well as to manipulate the emittance evolution in the half cell. By selecting a proper amplitude ratio and phase relationship between the first and second harmonic RF field components in the gun cavity, the superposition of the harmonic field components can provide a flat-top like RF profile to omitting the RF emittance component in the gun, while rise the RF breakdown threshold. The recent status of the Bimodal Electron Gun R&D is presented, including the designs of the novel two frequency RF structure and the simulation of the beam dynamic.

INTRODUCTION

For the next generation light source, high brightness beams with a very small transverse and longitudinal emittance in the 6D phase space are required. The beam quality is essentially set by its injector and electron source, like RMS transverse emittance. An improved injector beam quality will help ease the challenge for the downstream emittance manipulation using the bunch compression and emittance exchange, thus reduce the complexity of the accelerator system. Here, R&D efforts are described with the aim towards an implementation of a novel high-gradient dual-mode RF gun base on FEL application with the acronym BEGUN—Bimodal Electron Gun.

The transverse emittance of a RF gun is predominately determined by the RF, space charge and thermal emittance. The theory proposed by Kim [1] for single frequency RF guns, further developed by Serafini [2, 3] for multi-frequency RF guns, provides the basic analytic description of the emittance growth mechanisms in the RF guns. By selecting a proper amplitude ratio and phase relationship between the first and second harmonic RF field components

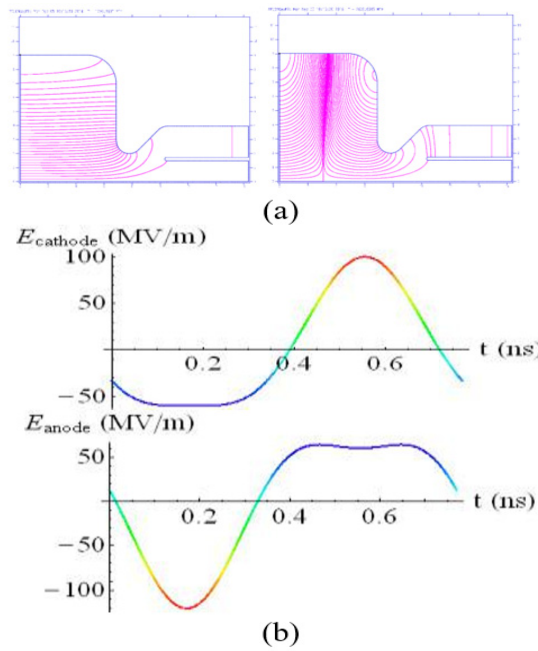

Figure 1: (a) The half-cell design of the BEGUN cavity using SUPERFISH, where the fundamental mode is TM010-like and the second harmonic mode is TM011-like. (b) Electric field amplitude of two-mode superpositions at the cathode (flat side) and anode (beam aperture), where the blue section of the curves indicates the rf electric field pointing into the metal surface (cathode-like field) and red for pointing out of the metal surface (anode-like field).

in the gun cavity, the superposition of the harmonic field components can provide a flat-top like RF profile to omitting the RF emittance component in the gun, while increase the RF breakdown threshold. This approach provides multiple control knobs over the cathode field, bunch length, and bunch charge density; and especially, the suppression RF nonlinearity. Once the electrons emitted from the cathode, the RF field increases rapidly in time to a flat-top, preserves the emittance against the rf emittance degradation. Serafini proposed a two-frequency RF gun configuration using the first harmonic plus an odd harmonic to cancel the

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RF emittance [2,3]. However as shown in Fig. 1, our study reveals that excitation of the TM010 mode at frequency f and the TM011 mode (TM012 –like if in a full cell) at the second harmonic frequency 2f driven by two external phase-locked RF sources, can neutralize the emittance degradation as well.

The two-frequency superposition also introduces the Anode-cathode effect [4] in the BEGUN cavity, where the RF -electric field pointing into one wall (a cathode-like field) is significantly smaller than the field pointing out of that wall (an anode-like field). A strong anode field will raise the work function barrier to suppress the field emission and secondary electron emission, which may lead to the RF break down. It also narrows the time duration of the peak field exposure and delocalizes the spatial distribution of the peak field during each RF cycle, which reduces the exposure time to the peak surface RF fields. The single cell design can avoid perturbation of the spurious zero-mode arising in multi-cell RF gun structures, rather than the desired π-mode. Further, a short overall gun length allows the magnetic coil to be located closer to the half-cell exit, and to provide full compatibility with magnetic fields required for the emittance compensation and/or flat-beam emittance partition. It is possible to have a direct translation of BEGUN concept into a high-repetition rate RF gun, similar to either superconducting RF gun [5] or VHF normal conducting RF gun [6]. This approach also allows a quick adjustment of the experimental configuration, such as the cavity frequency tuning and cathode replacement, so as to mitigate the R&D risk while exploring innovations.

BEGUN PERFORMANCE

By introducing a harmonic component of the RF fundamental field, the emittance degradation due to the RF emittance is significantly reduced. It enables a better RF gun performance and allows a broader application range for the different bunch charge, size and length requirement. To validate the BEGUN concept, bimodal RF guns together with a compensation coil have been modelled using ASTRA [7] simulations to benchmark the performance.

As an example, the simulation results presented here are for the dual-mode operation of a half-cell BEGUN operating at 2.856 GHz and 5712 GHz, as shown in Table 1. The 2.856 + 5.712 GHz BEGUN half-cell cavity supports the 2.856 GHz TM010 mode with a Q factor 14941, and the 5.712 GHz TM011 mode (TM012 if in full cell) with a Q factor 13883. The yokes are designed to cancel the stray magnetic field at the cathode surface and yet to provide a focusing magnetic field to compensate the emittance growth [8]. The injection phases and the field strengths of RF and compensation coil are scanned to minimize the transverse emittance.

Table 1: Summary of BEGUN Parameters

Parameters	**Single Mode**	**Double Mode**
Beam Energy (MeV)	2.93	2.45
RMS Transverse Emittance (norm. π mm rad)	0.55	0.47
RMS Longitudinal Emittance (norm. π mm rad)	14.58	11.60
Relative Energy Spread (%)	1.54	1.20
Bunch Size (mm)	0.16	0.24
Bunch Length (mm)	1.14	0.84

The optimized results, with the space charge effect, cathode mirror effect, and emittance compensation, are as follows: for the single mode case (fundamental mode only) the minimum RMS normalized transverse emittance is $\varepsilon x=0.55$ π mm mrad, the transverse bunch size is $\sigma x=0.17$ mm, normalized longitudinal emittance is $\varepsilon z=14.58$ π keV mm, with the beam energy E=2.93 MeV, energy spread of $\Delta E/E=1.54\%$, the peak cathode field in the fundamental mode is E1=120 MV/m, the peak axial magnetic field is Bz,max=0.57 T, and the injection phases is $\phi 1=200°$, RF power requirements is P1=3.35 MW at the fundamental frequency. For the bimodal case, the minimum RMS normalized transverse emittance is $\varepsilon x=0.45$ π mm mrad, the transverse bunch size is $\sigma x=0.23$ mm, normalized longitudinal emittance is $\varepsilon z=11.592$ π keV mm, with the beam energy E=2.45 MeV, energy spread of $\Delta E/E=1.20\%$, the peak cathode field in the fundamental mode is E1=120 MV/m and in the second harmonic mode is E2=30 MV/m, the peak axial magnetic field is Bz,max=0.52 T, and the injection phases is $\phi 1=205°$ and $\phi 2=250°$, RF power requirements is P1=3.35 MW at the fundamental frequency and P2=1.215 MW at the second harmonic frequency. To unify the parameter description to avoid ambiguity, the phase space distribution of a bunch generated at the cathode is described as follows: the bunch is taken as a round beam with uniform radial distribution having RMS transverse size $\sigma x,y=$ 0.38mm, uniform radial distribution of the transverse momentum, the longitudinal plateau distribution of pulse length Lt= 20 ps, rise time rt = 0.7ps, and a bunch charge of 0.25 nC, as the input parameters for ASTRA generator; and the initial intrinsic normalized transverse emittance is $\varepsilon x=0.47$ π mm mrad. Different spatial distribution such as truncated-Gaussian [9] and bunch charge may give better optimization results.

Significant improvement over the transverse bunch distribution, emittance and energy spread is observed in the two-mode superposition as compared to the single mode operation of the BEGUN. In Fig. 2, the evolution of transverse emittance, transverse size, longitudinal emittance and energy of bimodal gun are plotted, showing the improvement of the bimodal gun.

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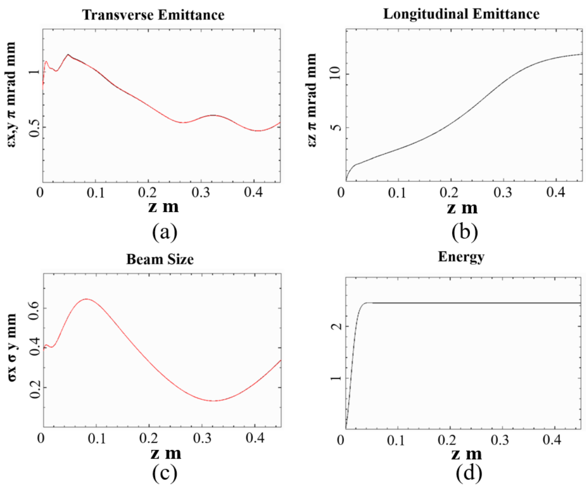

Figure 2: Beam dynamic performance of S-band/C-band BEGUN with bunch charge 0.25 nC as results of ASTRA simulation. The evolution of (a) the transverse emittance εx, (b) the longitudinal emittance εz, (c) the transverse beam size σx, and (d) the beam energy is shown along the axis of BEGUN.

In Fig. 3, the transverse phase space, slice emittance and relative energy spectrum are plotted with ASTRA. The transverse phase space of bimodal gun is more compact, while in single mode gun electrons at the marginal area have a relatively large transvers momentum angle. This is also shown in the slice emittance plot. Due to the flat-top effect, the bimodal slice emittance is more aligned than the single mode. The energy spectrum also improved by the bimodal gun.

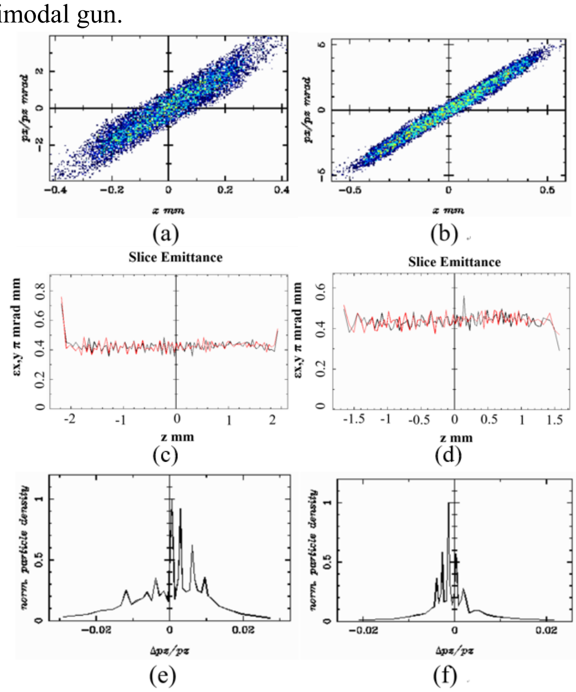

Figure 3: Beam dynamic performance of S-band/C-band BEGUN with bunch charge 0.25 nC as results of ASTRA simulation. transverse phase space px-x of (a) single mode, (b) double mode, slice emittance of (c) single mode, (d) double mode, energy spectrum of (e) single mode, (f) double mode.

ENGINEERING DESIGN AND EXPERIMENTAL EFFORTS

The experimental setup is illustrated in Fig. 4. The dual-frequency mutually-phase-coherent multi-MW RF source at 2.856 GHz and 5.712 GHz that will be available for experiments is under construction at Yale Beam Physics Lab. This multi-harmonic RF source is a unique facility, built to provide mutually phase-locked multi-MW ~1 μs pulses at 2.856 and 5.712 GHz with continuously-adjustable amplitudes and relative phase difference [10]. An S-band waveguide transmission line has the provision for the power splitting into two portions with an adjustable amplitude and phase, one portion driving a second-harmonic frequency multiplier to produce the C-band power, and the rest to transmit the S-band power. The bimodal BEGUN cavity can then be driven with the phase-synchronous power simultaneously at S-band and C-band, with fully-adjustable power levels and relative phase difference.

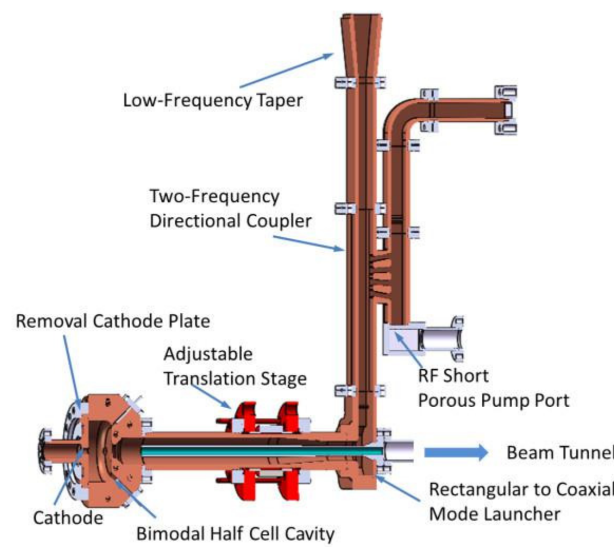

Figure 4: Engineering drawing of the BEGUN system.

CONCLUSION

The affirmative verification by theory and simulation establishes the feasibility of the BEGUN concept. Significant improvement over the transverse emittance and energy spread is observed in the two-mode superposition as compared to the single mode operation of the BEGUN. Given the potential benefits addressed here, the beam quality improvement and cost saving for the overall light source system might outweigh the cost of an additional power source and the complexity of the two-frequency system.

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