HIGH BRIGHTNESS THERMIONIC ELECTRON GUN PERFORMANCE

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Abstract

Commercial Off-The-Shelf (COTS) gridded thermionic cathode electron guns show promise for certain pulsed and CW electron beam applications. Accelerator systems utilizing these guns are presently being commissioned for pulse mode operation. Beam has been delivered to the IR wiggler of the Free Electron Laser (FEL) at the Fritz Haber Institute (FHI) der Max Planck Gesellschaft in Berlin [1] in advance of their October 28 Centennial. In the course of commissioning, we have performed emittance measurements that indicate the beam transverse rms emittance is 8-10mm-mrad at 20kV, consistent with our gun simulations. The nominal system operating voltage is 45kV. We have also studied the dependence of the extracted current as a function of RF power. After the initial low-level region, near linear behaviour is observed. The maximum value achieved was 806mA at 23.2kV and ~200W input RF, limited only by our available power supply. We find that pulsed beam applications must address the DC idle current that leaks from the cathode by utilizing grid or cathode pulsing. S-band systems are being commissioned at this time using both approaches. Lower frequency CW mode operation has also been proposed for high-power Energy Recovering Linacs (ERL) and FELs [2]. The above performance measurements indicate that adequate high-current thermionic gun beam quality is possible for IR FELs in such CW operation. The next step for this application, which is already in progress, is the design and testing of a gun with a normal-conducting pre-booster incorporating solenoid focusing. This will raise the output energy to greater than 1 MeV so that the performance of the concept can be evaluated. The design must also consider ways to ameliorate beam scraping. Because the present COTS gun [3] is capable of delivering 5A, which greatly exceeds the requirements of all these applications, both CW and pulsed operation would benefit greatly from a redesigned gun with a smaller cathode and a reduced radius or totally eliminated cathode "hole". It remains to be seen if totally eliminating the "hole" is possible while maintaining a robust gun HV and RF design in the presence of ion back bombardment.

INTRODUCTION

Standard thermionic guns for accelerator applications require complex, real-estate-consuming, bunching systems in order to produce high-quality electron beams and achieve low electron beam loss in the accelerating structures. Photocathode guns can be used to provide pre-modulated electron beams, but have not yet been shown to be practical for high-power CW systems, due principally to cathode lifetime issues at high current. In addition, they add their own, significant complexities to the system through the addition of the photocathode drive laser and the need for maintaining very good vacuum levels in the guns to avoid poisoning the cathodes. A gridded thermionic electron gun can provide a robust, economical, and compact solution to the provision of the high-performance, high-power electron beams required, when the grid is driven by an RF signal at the desired bunch

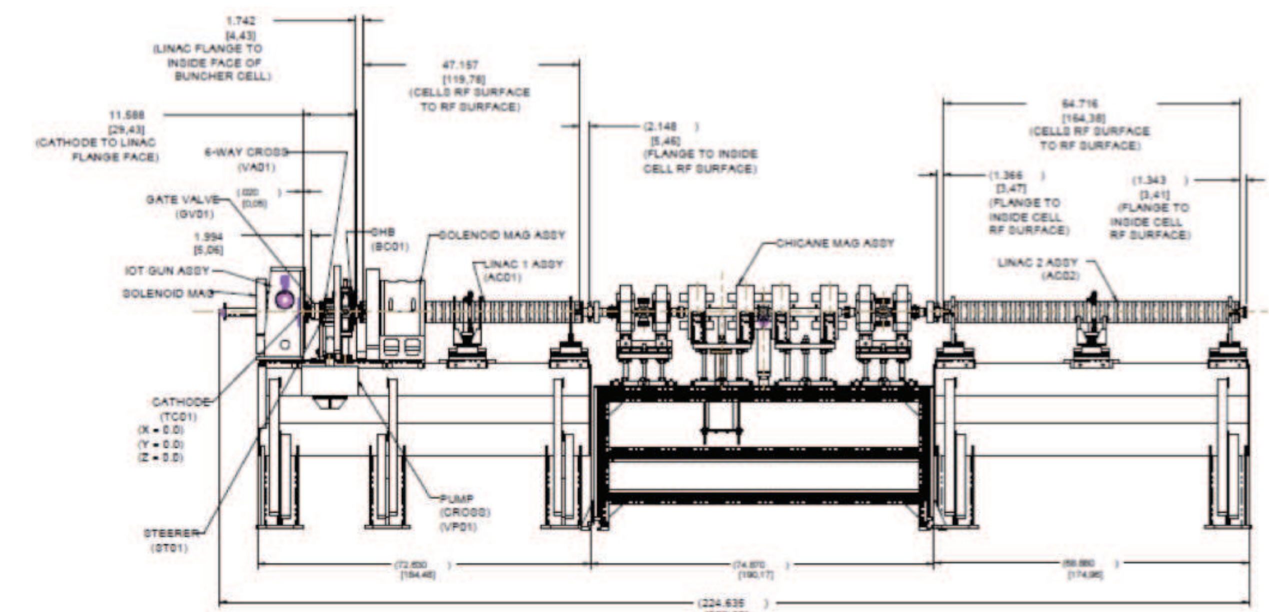

Figure 1: Layout of the FHI accelerator section from the gridded gun (left) to the second linac output (right).

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frequency. Such a gun could find application in ERLs, compact FELs, and other areas that would benefit from a high-performance compact accelerator system. Two such guns are presently in use in AES accelerator systems [4], with one of them driving the FHI infrared FEL [5,6]. The layout of this accelerator for this device is shown in Figure 1.

The FEL consists of a 50MeV accelerator driven by a gridded thermionic gun with a beam transport system that feeds two undulators and a diagnostic beamline as shown in the schematic diagram of Figure 2. Two 2.998GHz S-band, normal-conducting electron linacs and the gun-to-dump electron beam lines have been designed, fabricated, and installed by AES. The first linac accelerates the electron bunches to a nominal energy of 20 MeV, while the second one accelerates or decelerates the electrons to deliver any final energy between 15 and 50 MeV. A chicane between the structures allows for adjustment of the bunch length as required. A number of measurements and simulations have been performed on the gun indicating its potential for use in high-current, high-performance applications. Another group has also proposed using an identical gun for high-power ERLs and FELs [2].

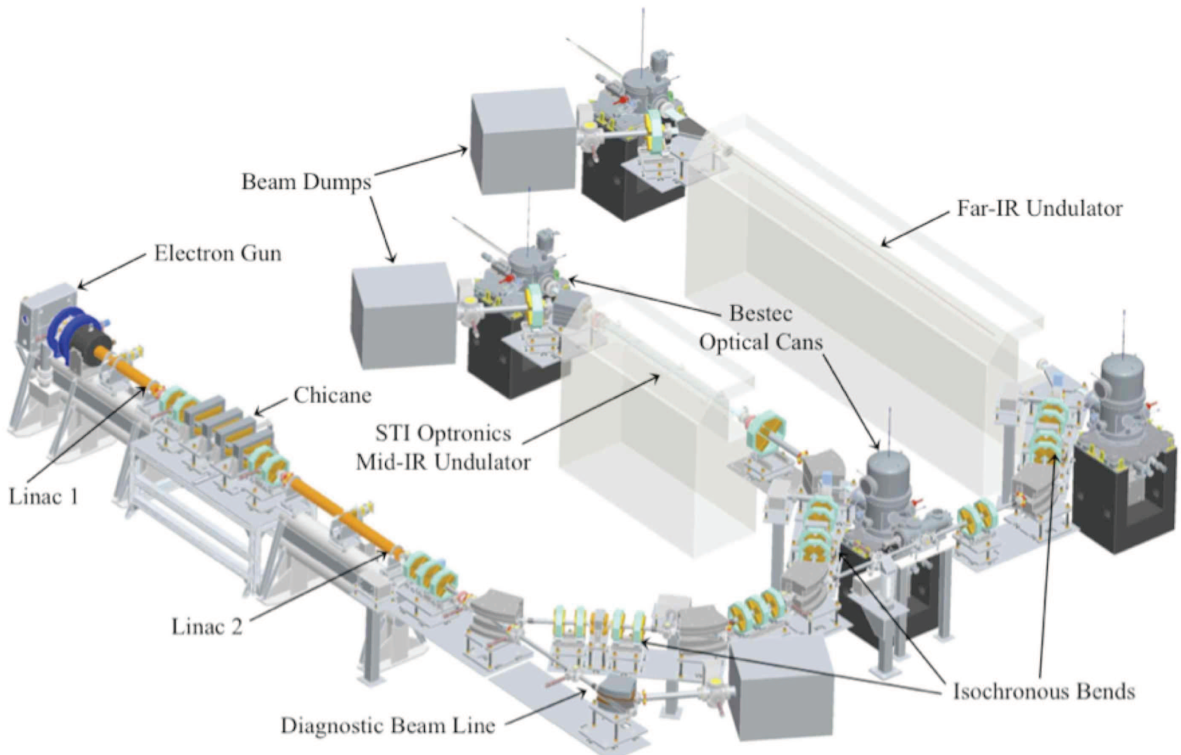

Figure 2: Schematic diagram of the FHI IR & THz FEL.

INJECTOR DESIGN AND MODELING

Since the present guns are being used in conjunction with S-band accelerators, the RF drive to the gun is a sub-harmonic of the main 2.998 GHz accelerating frequency. Driving the grid at the third sub-harmonic produces a bunch length that is still too long for efficient capture so a sub-harmonic cavity is used to further compress the bunch length. The front-end design is shown in Figure 3. Solenoid focusing is required to confine the beam in this front-end section. Solenoid 1 in Figure 3 is a bucking coil to ensure zero magnetic field on the cathode.

We have performed simulations of this system. The RF fields with the biased gun grid are shown in Figure 4. The cathode is to the left and the anode to the right. The insert in the upper right is the axial solenoidal field employed. Figure 5 shows a TStep [7] simulation of bunch formation where the beam pulse streaming through the grid can clearly be seen in the upper radial projection. We find there is a correlation between longitudinal beam position and cathode birth location in that electrons emitted at larger radius populate the front of the bunch and those emitted nearer the axis trail the bunch. The same behaviour is reported by Ref. [2]. In order to meet the FHI performance specifications of Table 1, it is necessary for us to scrape some of the electrons that populate the tail and the outer radii due to the unnecessary large diameter of the cathode. The key performance parameters from Table 1 at 50MeV and for a 200pC bunch are a transverse emittance < 20mm-mrad and longitudinal emittance ~ 50keV-psec. The latter requirement is particularly stressing but we achieve it in simulations.

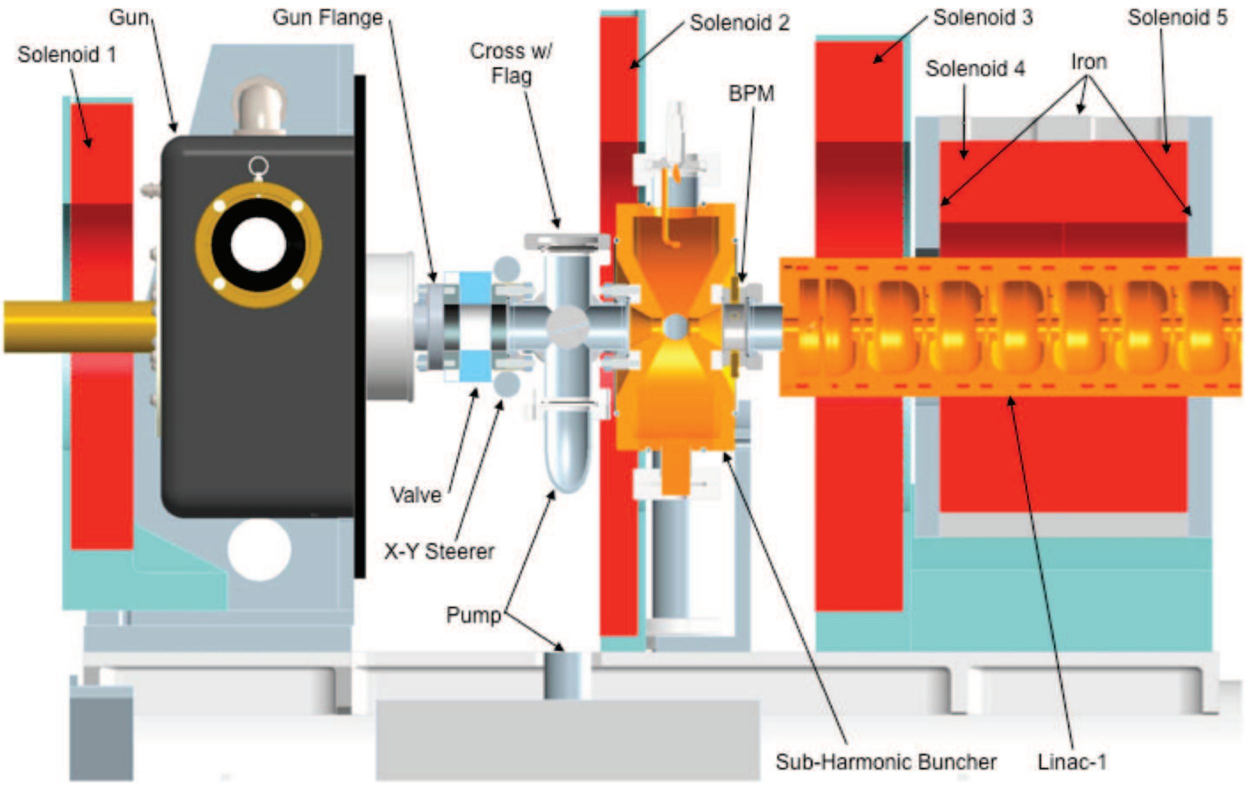

Figure 3: FHI FEL front-end configuration.

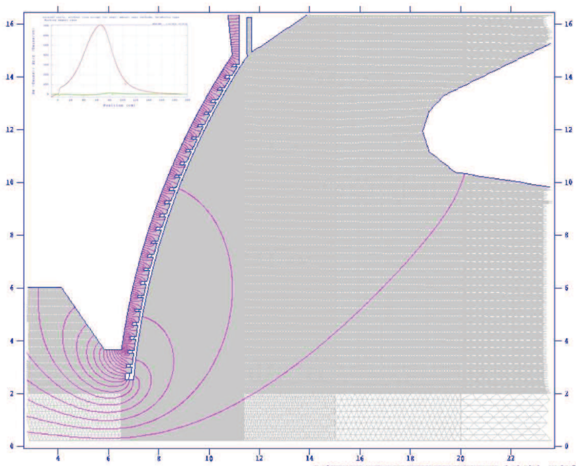

Figure 4: Gun biased grid RF fields.

Table 1: FHI FEL Electron Beam Parameters

Parameter	Unit	Specification	Target
Electron Energy	MeV	20 - 50	15 - 50
Energy Spread	keV	50	< 50
Energy Drift per Hour	%	0.1	< 0.1
Charge per Pulse	pC	200	> 200
Micropulse Length	psec	1 - 5	1 - 10
Micropulse Repetition Rate	GHz	1	1 & 3
Micropulse Jitter	psec	0.5	0.1
Macropulse Length	µsec	1 - 8	1 - 15
Macropulse Repitition Rate	Hz	10	20
Normalized rms Transverse Emittance	π mm-mrad	20	20

Figure 6 shows the delivered bunch at the end of the second linac with 3% of the bunch tail scrapped off. Upper left and right are the horizontal and vertical phase spaces respectively. The lower left and right are the transverse bunch distribution and the longitudinal phase space. Figure 7 reproduces the two lower plots of Figure 6 but projects out the longitudinal axial bunch and energy profiles.

In pulsed operation, we have measured 4mm-mrad transverse rms emittance at 14kV and 26mA. At 20kV and 100mA we obtained 8mm-mrad. Measurements at 45kV will be made shortly. Operation in this CW HV mode was limited by the available power supplies and the idle current produced by the gun. The idle current consists of electrons leaking through or around the grid when the HV is on even though the grid is biased negatively. There can be considerable power in the idle current. This is obviously not an issue in CW operation and is only a concern in macropulse operation mode.

GUN PERFORMANCE IN PULSED MODE

Figure 8 shows the beam current as a function of grid RF power at lower levels of RF power. At 23.2kV we achieved 806mA with ~200W of RF grid power. Recently, at FHI, we achieved ~600mA with 200W of RF grid power at 45kV. Here, in both cases, we are only are limited by the available 200W of our RF power supplies.

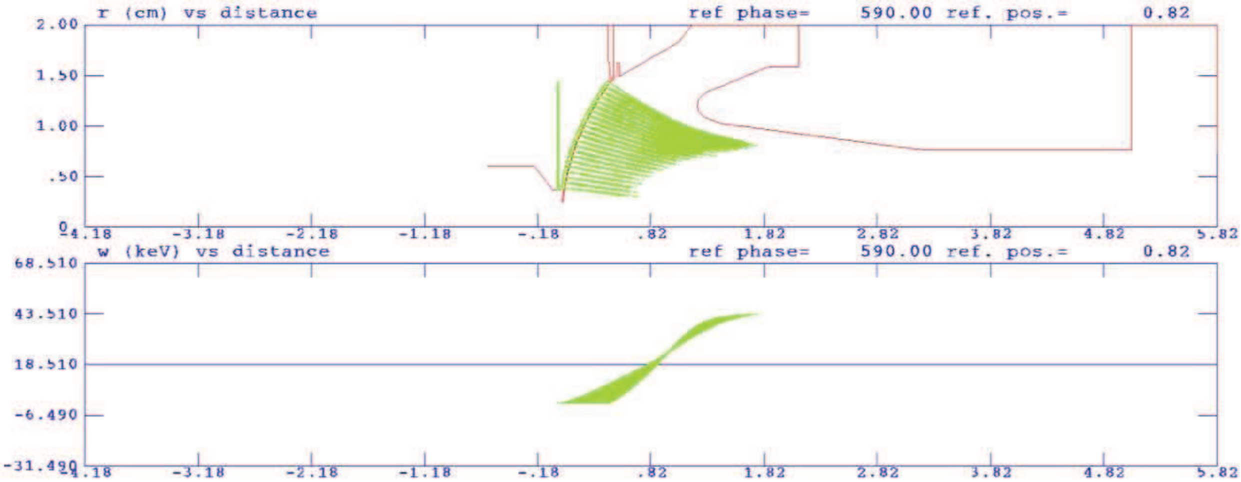

Figure 5: TStep radial projection (upper) and energy profile (lower) during bunch formation from the gun.

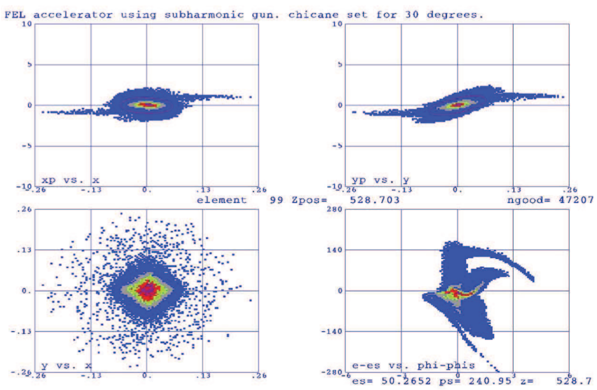

Figure 6: Phase space bunch profiles after the second linac.

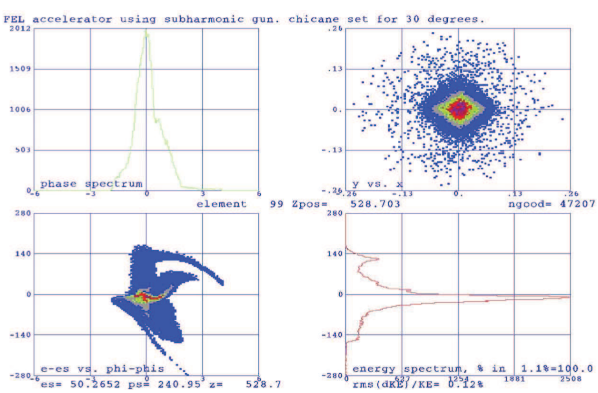

Figure 7: Longitudinal axial bunch and energy profiles after the second linac.

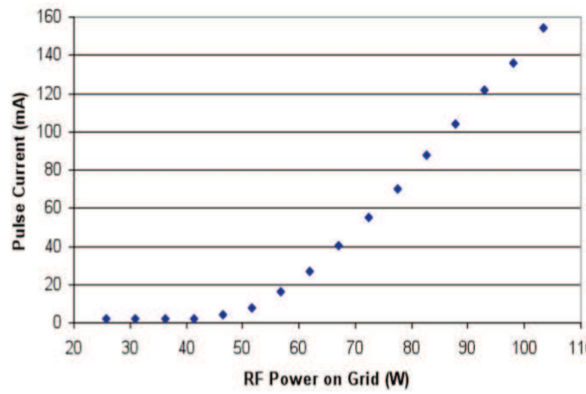

Figure 8: Pulse current with RF power on the grid.

Figure 9 shows the installed front end of the FHI system that corresponds to Figure 2. Unfortunately, the orientation is inverted here with the gun to the right.

We have delivered beam to the FHI mid-IR beamline dump. Figure 10 shows the grid and heated cathode as imaged off the OTR screen before the first Linac. Figure 11 shows the beam imaged on this same screen.

HIGH-POWER ELECTRON INJECTORS

We have noted that Sprangle et al. [2] have proposed using such an electron source for high-power ERLs and FELs. Under these conditions, desired of future light sources and other systems, the reliability and power required of a photocathode drive laser is suspect, as are photocathode lifetimes at high-currents [8], given their high vacuum requirements.

In contrast, thermionic guns have demonstrated the required currents and operate comfortably with achievable vacuum levels in the 10^{-8} Torr range. In this case we have to prove two things. Firstly, we must demonstrate that we can deliver the necessary beam quality for the application in question, in terms of transverse and longitudinal emittance. The reason photocathode systems have been preferred to date is that their achieved beam quality has been measurably better than thermionic systems. However, the intrinsic beam quality achievable with thermionic systems, (< 10mm-mrad, < 100keV-psec) is sufficient for some high-power applications such as IR FELs.

Secondly, we must demonstrate that we can entrain almost all of the emitted electrons in the bunch, since beam spill at high-power cannot be tolerated in a high-power accelerator system.

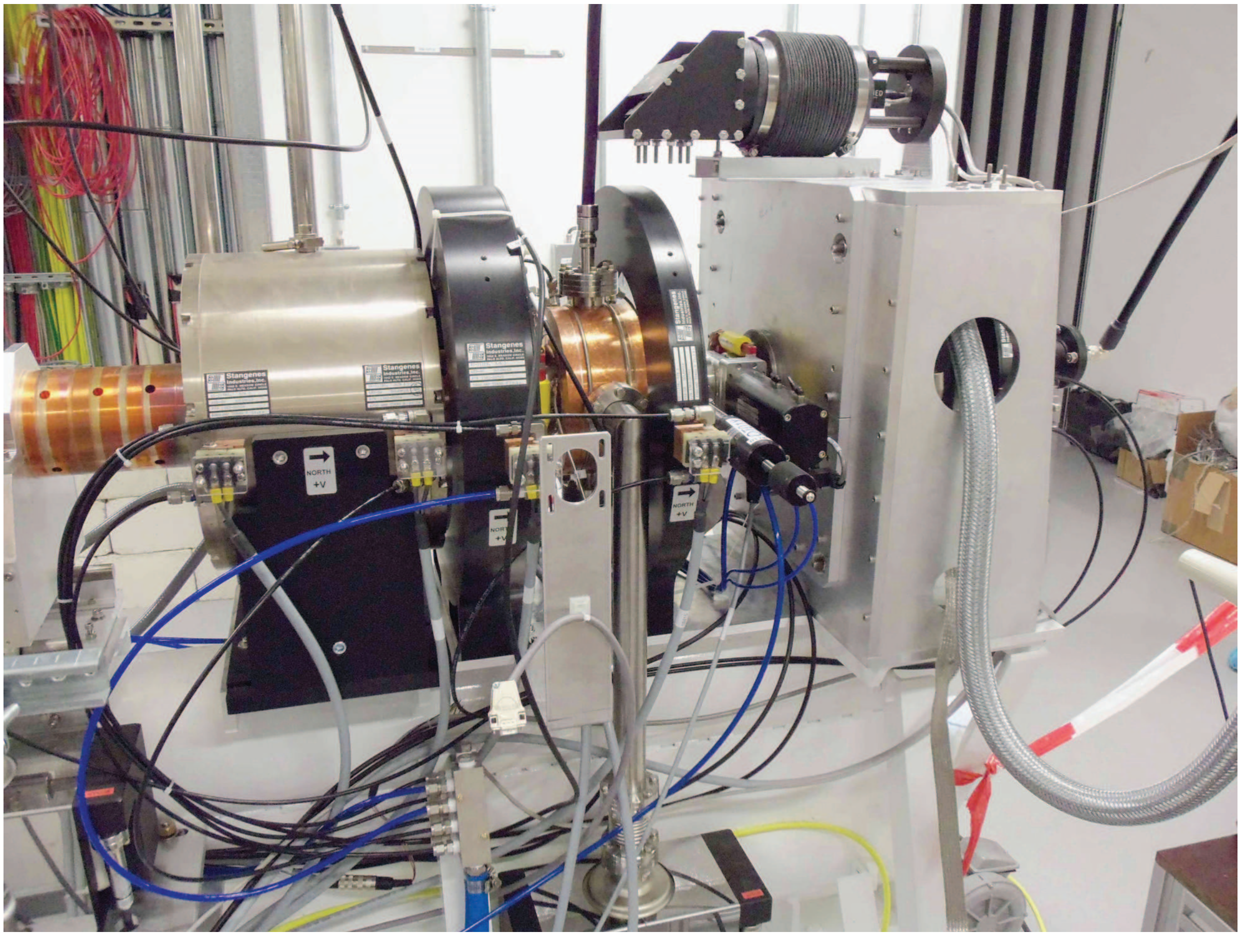

Figure 9: FHI gun, sub-harmonic buncher and first linac as installed in Berlin.

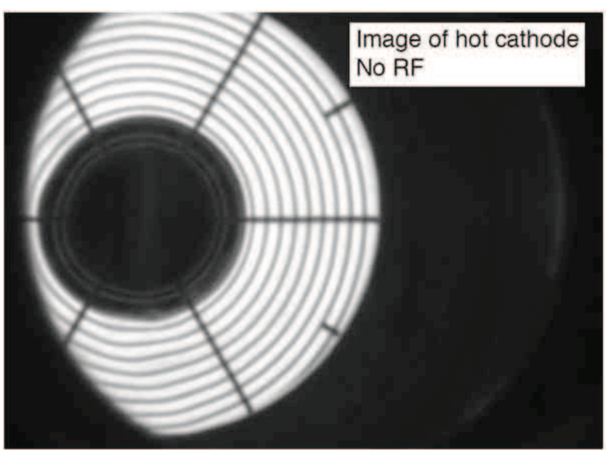

Figure 10: Gun filament and grid.

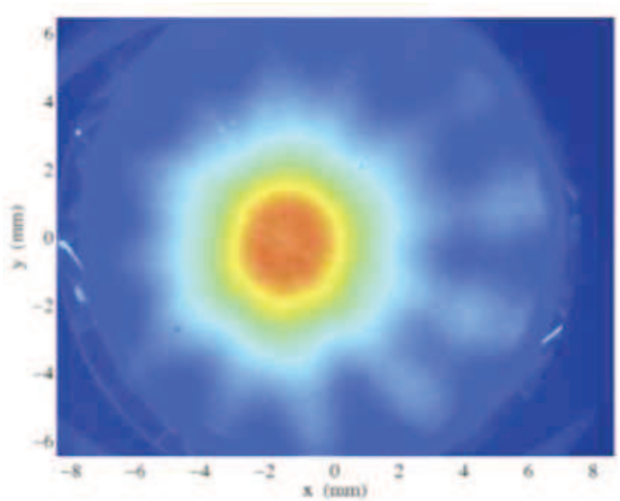

Figure 11: Beam imaged after the gun with the solenoids set for zero field on the cathode.

Figure 12, reproduced courtesy of Ref. [2], illustrates the concept. Firstly, they propose using both the fundamental RF frequency and the third harmonic on the gun grid to sharpen up the RF bucket and shorten the delivered electron bunch. This is illustrated in the lower right of Figure 12.

A bunch is produced by the gun and rapidly captured in a pre-booster cavity closely coupled to the gridded gun. A one and a half cell pre-booster is shown here. RF bunch compression is arranged in the first half-cell of the pre-booster. The Ref. [2] simulations indicate that performance meeting the beam quality targets we need, can be achieved.

We have begun the physics and engineering design of such a close-coupled pre-booster and gridded gun. Our initial analysis indicates that a simply-cooled copper cavity can be produced to validate this concept. We are proceeding to develop this work with a view to delivering a high-current > 1MeV electron beam for experimental performance measurements.

The lower left insert in Figure 12 shows the typical grid dimensions of the gun we are using. This gun can produce 5A, far exceeding the requirements of any of the applications in question. Consequently, given the observation of the correlation between birth radius and axial bunch position of the electrons, we would expect better beam quality and electron entrainment to be achieved, not only in transverse phase space but also in longitudinal phase space, if we were to reduce the active size of the grid and cathode and reduce or eliminate the central hole in the grid as suggested by Ref. [2]. Whether the hole can be completely eliminated in the presence of ion back bombardment is to be determined. Hence, the electron source solution we seek is not precisely a COTS product but rather a slightly modified version for our applications.

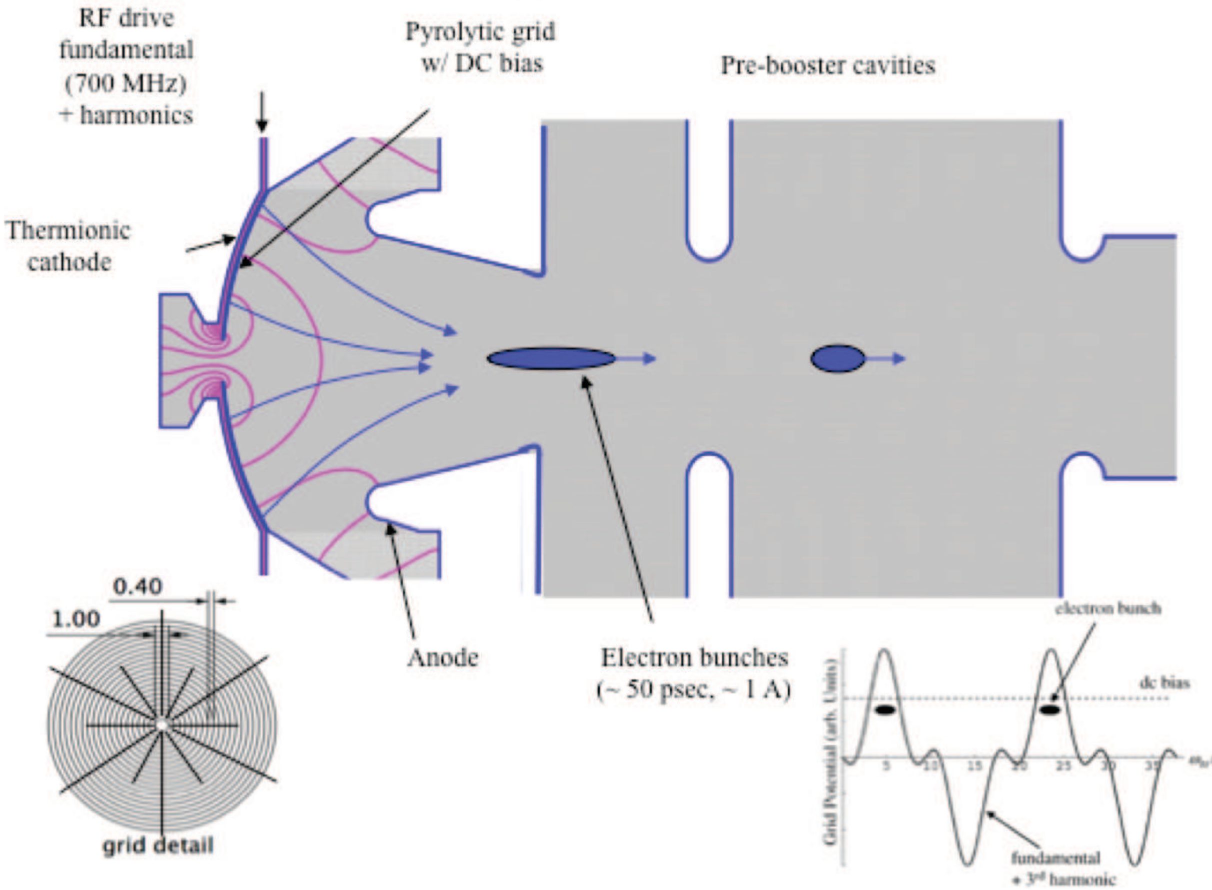

Figure 12: Ref [2] concept for a high-power gridded gun and pre-booster electron injector system.

SUMMARY

COTS gridded thermionic cathode electron guns are being used for two accelerator systems that are presently being commissioned by AES. One is an IR and THz FEL and the other is a system for contraband detection. The predicted performance meets the requirements of the two systems and exceeds the performance of conventional DC gun designs within a more compact footprint. We are presently validating the predicted performance but initial results indicate we will meet the project targets. Lower frequency CW mode operation has also been proposed for high-power ERLs and FELs. We are presently designing a pre-booster/gun combination to measure and validate the performance of such an injector.

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