

A CW normal-conductive RF gun for free electron laser and energy recovery linac applications

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Abstract

Currently proposed energy recovery linac and high average power free electron laser projects require electron beam sources that can generate up to ~ 1 nC bunch charges with less than 1 mm mrad normalized emittance at high repetition rates (greater than ~ 1 MHz). Proposed sources are based around either high voltage DC or microwave RF guns, each with its particular set of technological limits and system complications. We propose an approach for a gun fully based on mature RF and mechanical technology that greatly diminishes many of such complications. The concepts for such a source as well as the present RF and mechanical design are described. Simulations that demonstrate the beam quality preservation and transport capability of an injector scheme based on such a gun are also presented.

Key words: electron source, low emittance, high brightness, ERL-FEL Injector

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1. Introduction

A number of proposed projects in energy recovery linacs (ERL) and linac-based soft-xray-VUV free electron lasers (FEL) requires injection of 100 pC - 1 nC electron bunches at repetition rates from kHz to hundreds of MHz [1, 2, 3, 4, 5, 6, 7]. For both ERL and FEL applications, production of high-brightness electron beams is critical in achieving the desired x-ray performance and normalized beam emittances lower than 1 mm mrad are required. This places particular burdens on the cathode, gun and injector systems. Limiting early emittance growth requires minimum accelerating electric fields in the gun of ~ 20 MV/m and gun voltages of ~ 500 kV or higher [8]. Obtaining these fields and voltages in a DC gun requires a significant effort and expertise, especially in preventing insulator breakdown. Voltages of up to ~ 350 kV have been already demonstrated [9] and there is a group trying to extend such a value up to ~ 750 kV [10].

Superconducting, high-frequency cavities are likely candidates for high repetition rate photoinjectors, and an intense R&D activity around the world is presently

directed to demonstrate the capability of such a scheme to operate with the required performances [11, 12]. Superconducting technology for guns is not yet mature and additionally is not compatible with many cathode materials. Moreover, it prevents by flux exclusion (Meissner effect) the application of controlled magnetic fields at the cathode for emittance manipulation techniques [13, 14]. High-frequency (L- to S-band) normal-conducting radio-frequency (RF) guns do not present such limitations; however, the average power density in the cavity structure limits the practical repetition rate to the kHz range [15]. By decreasing the RF frequency, the size of the cavities increases with a beneficial reduction of the power density on the structure walls. In this situation, the repetition rate of the system can increase and continuous wave (CW) operation can be achieved. The Boeing gun has achieved 25% duty cycle operation at 433 MHz [16], a 700 MHz CW normal conducting gun has been proposed [17], and a group at Los Alamos is completing the construction of a 700 MHz normal-conducting RF gun where a sophisticated and state of the art cooling system has been designed to operate in CW mode [18, 19].

In our approach [20, 21, 22], based on an idea of J. Staples and developed at the Lawrence Berkeley National Laboratory in the framework of the activities

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on next generation light sources [23, 1], we lower the frequency further down into the Very High Frequency (VHF) range (30-300 MHz) adopting a design with a cavity operating at ~ 100 MHz. The resulting modest power load on the walls is compatible with the use of conventional technology for cooling the structure and makes it capable to operate in CW mode at 750 kV across the accelerating gap with a 20 MV/m gradient. The relatively large size of the cavity and the long RF wavelength allow the design of an efficient vacuum system with large pumping apertures capable of pressures compatible with the operation of many kind of cathode materials including semiconductors. An imbedded solenoid permits the easy control of the magnetic field in the cathode area. The choice of the frequency right in the middle of the FM broadcast band ensures the availability of commercial RF power sources. Many experiments utilizing pump-probe techniques require pulses to arrive at repetition rates in the 1 kHz - 1 MHz range. Our CW VHF-gun combined with the use of high quantum efficiency cathodes and relatively modest power laser systems can be, therefore, used as the main component for the injector of an FEL to readily serve this extremely active experimental community.

A similar concept that has been proven in operations is the VHF gun used at the ELSA 19 MeV linac [24, 25, 26], in which the 144 MHz gun has produced high charge-low emittance beams within a 150 μ s macropulse at 10 Hz repetition rate.

In the next sections, we describe the design concept of the VHF gun and the technical design solutions adopted. We also provide an example of a beam dynamics simulation showing the capability of such an injector to preserve the beam quality as required for FEL or ERL operation.

2. The VHF RF Gun System

The overall design of the gun is dictated by requirements of beam dynamics to produce the desired electron beam parameters, maximizing the shunt impedance to minimize the RF power requirement, minimizing the power density on the walls, allowing access for water cooling passages near high power density regions, minimizing field emission and multipactoring, and allowing for high conductance vacuum pumping.

Beam dynamics issues will be treated in section 3. Here we concentrate our attention on the engineering questions related to the design of the VHF gun. But before doing that, we note that the ~ 10 ns RF period is a relatively long time when compared with either the typical (few tens of ps) bunch length or the few hundreds of

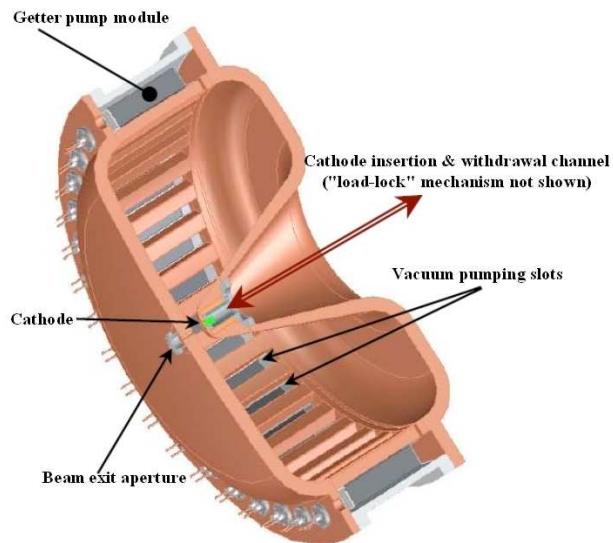


Figure 1:

ps beam transit time through the cavity gap. This makes the beam dynamics of the VHF gun similar to that of a DC gun. Extensive simulations [8] showed that the required beam performance can be obtained with DC fields of ~ 20 MV/m and with energy out of the gun greater than ~ 500 kV. In our design we exploit these results and assume 20 MV/m and 750 kV as the nominal values for the accelerating field and for the final energy respectively.

Figure 1 shows a 3-D view of the RF structure, while Table 1 contains the cavity main parameters. The normal-conducting structure will be fabricated from copper-plated steel and the re-entrant geometry allows for the desired resonant frequency while keeping the size of the whole structure reasonably small. The steel structure presents a better strength to weight ratio and is less expensive respect to the solid copper option, and the copper plated surface can achieve RF and vacuum performances at the same level of the solid copper case when the proper technology is used [28, 29].

The cavity geometry was carefully optimized to maximize the shunt impedance, to minimize the wall power density, to reduce the mechanical stress, simplify fabrication and facilitate photocathode replacement. At the nominal quality factor $Q_0 = 37800$, the cavity requires an RF power of 73 kW for an accelerating gradient of ~ 20 MV/m at the cathode and ~ 17.5 MV/m average over a gap of 4 cm for a final beam voltage of 750 kV. The modest 8 W/cm² maximum power density on the cavity walls is readily dissipated with conventional water

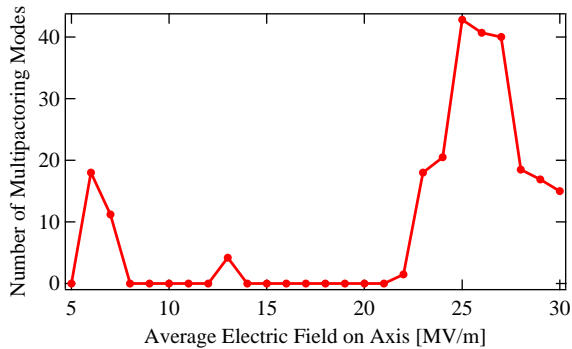


Figure 2:

cooling systems.

To provide 20 MV/m at the cathode, the maximum surface electric field at any point in the cavity is approximately 26 MV/m. Experience with existing RF structures suggests that such low fields should induce negligible field emission after conditioning if the proper construction techniques, materials and tolerances are used.

The maximum electric field of 26 MV/m should not represent difficulties with respect to voltage breakdown. For comparison, the similar frequency 144 MHz ELSA injector has been routinely operated with a 150 μ s pulse at 33 MV/m peak field with no serious breakdown [25], and in more recent times, the same injector successfully operated at 25% higher values (41 MV/m) [27].

To operate at the nominal voltage of 750 MV, a stored energy in the RF structure of 4.1 J is required. This value does not represent a concern for cavity wall damage even in the case of severe voltage breakdowns in which the energy can be entirely released during an arc.

Multipactoring is a complex phenomenon. For any frequency choice there are always RF power levels that excite potentially dangerous multipactoring resonances. An analysis of the phenomenon for our VHF structure has been performed by using two independent codes (Fishpact and AnalystTM [30, 31]) and indicates that there are no multipactoring modes in the region around the expected operating voltage. Figure 2 shows a summary of the Fishpact calculations. Two multipactoring regions exist at two low field levels, corresponding to 6 and 13 MV/m, and more significant at levels above 22 MV/m. The region from 14 to 21 MV/m does not show resonances, in particular at the field of 18.75 MV/m corresponding to our nominal gap voltage of 750 kV [32].

An additional advantage of VHF structures with respect to their higher frequency counterparts is in the geometry of the RF power input coupler. For the VHF

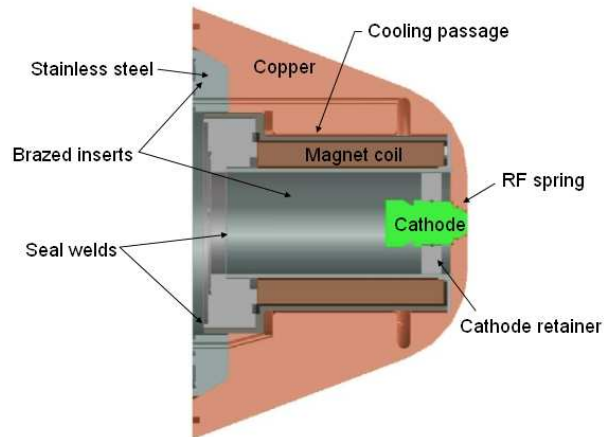


Figure 3:

case, a simple scheme with one or more loops can be used to feed the RF power into the structure. Loops introduce minimal distortion of the cavity fields (important from the beam dynamics point of view), and are easy to design, fabricate, and tune. For frequencies higher than VHF, the loop size decreases and the power dissipation in the loop can become too large. Ultimately a coupling iris must be used for higher frequencies with a consequent increase in design complexity and field distortion. For the case of the 106 MHz structure, one or two drive loops will provide sufficient RF power.

Figure 3 shows the detail of the VHF gun cathode area designed to operate with a load-lock mechanism (for easy, in-vacuum replacement of photocathodes) based on the FLASH gun design [33, 34]. A solenoidal coil is embedded in the 'nose' of the cavity and can be used to either null the on-axis magnetic flux, or to provide up to ~ 0.05 T at the cathode plane to create correlations in the emitted beam phase space that could be required by emittance exchange techniques [14, 13].

The VHF cavity has a relatively large volume to pump out; however, the long wavelength allows for large vacuum ports and consequently for better pumping speed. Design of 36 pumping slots, 4.9 cm wide separated by bars also 4.9 cm wide, around the cavity equator have been assessed; their impact on RF performance is negligible [35, 36]. The frequency shift due to the presence of the slots is very small. Likewise, the increase in the RF power required is also small. Figure 4 shows a MAFIA code [37] simulation illustrating the logarithm of the magnitude of the electric field in the outer pump slot region of cavity expressed in dB. The attenuation of the field along the depth of

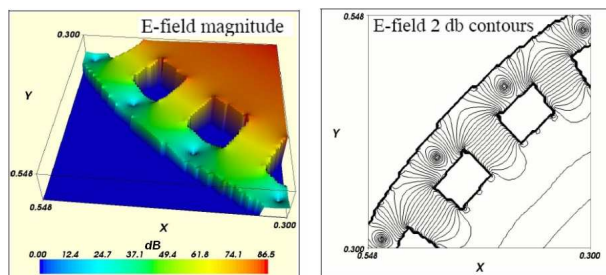


Figure 4:

the slot is seen to be about 30 contours, or 60 dB, consistent with a waveguide-beyond-cutoff. Calculation of the magnetic field (not shown) gives identical results in the slots. There is a local minimum in the field magnitude at points directly behind the bars, which are a good spot for getter pumps to be located. The RF power absorbed by a getter pump module in this position has been estimated to be ~ 1 W. The large anode wall is slightly curved to provide greater stiffness against deflection under vacuum. An all-metal structure is suitable for bake-out procedures, and the large outer diameter provides excellent accessibility for the getter pumps. Initial calculations using the SAES getter wafer modules WP1250/2 [38] have shown that the cavity should support a vacuum down to the high 10^{-9} Pa (10^{-11} Torr) range. Depending on the fabrication technique, some of the getter modules can potentially generate microparticles (dust) during operation. Such a situation could trigger voltage breakdown in the cavity and must be avoided. The final decision on the getter module to be used will be made only after a careful investigation of the issue.

The VHF frequency cavity is larger than the S and L band counterparts and the longer RF wavelength relaxes the mechanical tolerance and surface roughness requirements. Thermal and structural analysis of the cavity has been performed as well. Surface heat loads derived from the SUPERFISH code [39] were used as input to the ANSYS FEA code [40] and applied to an accurate CAD model of one quadrant of the gun cavity. Figure 5 shows a contained maximum temperature increase of ~ 83 °C in the center of the central cone, and a much smaller increase at the cathode area. This temperature variation does not represent a concern from either the mechanical or the RF point of view. The associated mechanical stress is quite small and the cavity frequency at thermal equilibrium will be regulated by the tuning system described later in this section. Cooling is provided by water passages in machined struc-

tures brazed to the exterior of the cavity in high heat load regions and by brazed-on cooling tubes in the low heat regions. The greatest temperature rise experienced at the center of the central cone of the cavity, is due primarily to the increased thickness of steel separating the heated surface from the exterior cooled surface in this area. A two-temperature frequency regulation system will be applied, one to the outer wall, and the other to the cone, instead of movable tuners, to control the resonance. The coarse frequency will be set at manufacturing time, with the installation of small perturbers in the back wall.

The temperature distribution in combination with the vacuum (pressure) load was applied to the FEA model to determine the stress in the cavity and the distortion under load. The peak stress is less than 155 MPa (a conservative 40% of the maximum yield strength of AISI 1020 steel) while the critical acceleration gap changes by a modest 0.17 mm (0.4%).

The beam exit hole and pipe diameter is presently set at 2.5 cm. Such a pipe size is compatible with a geometry like the one used, for example, in the PITZ photoinjector [41]. In this kind of scheme, a ~ 45 deg mirror, located along the beam pipe downstream the gun, allows to direct the laser beam almost perpendicularly to the cathode surface. We are also evaluating the possibility of illuminating the cathode with a smaller angle of incidence respect to its plane (laser port on the exit wall of the cavity). The decision for the final configuration will account for the cathode performance as well as for other possible effects such as wakefields induced by the laser mirror [41, 42], or cavity field perturbation due to the laser ports.

3. Beam Dynamics Simulations

In order to control space charge effects in a similar manner to the approach taken for DC guns, the VHF gun is designed to deliver a relatively long electron bunch of several tens of picoseconds. This bunch is delivered to an injection system for additional acceleration, bunch compression, and emittance compensation/manipulation prior to further acceleration and injection into undulators.

We simulated the VHF gun performance by using the Advanced Photoinjector EXperiment (APEX) layout. APEX is a Lawrence Berkeley National Laboratory proposal for a beamline conceived to address fundamental issues in high average current, high brightness beam production for soft x-ray FEL applications.

The APEX layout is schematically shown in Fig. 6. A UHF single-cell buncher, receives the 750 kV beam

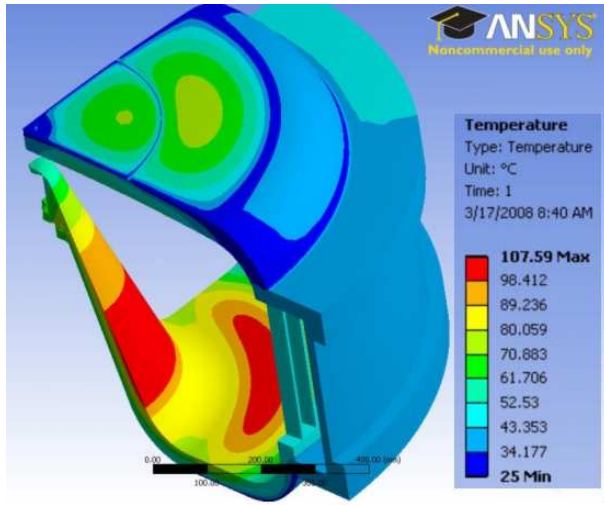


Figure 5:

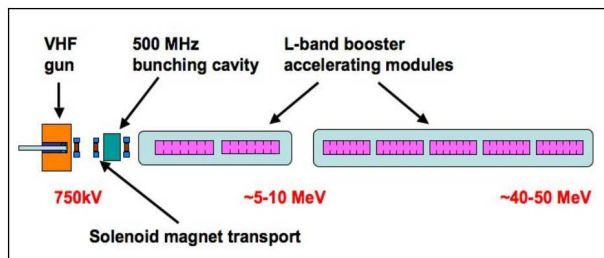


Figure 6:

from the VHF gun and introduces an energy chirp to allow compression of the beam. A L-band pre-booster then takes the mildly relativistic 750 kV beam and accelerates it to the relativistic energy of ~ 10 MeV, while completing the longitudinal compression and the matching of the transverse beam parameters necessary for the complete emittance compensation [43, 44]. The last L-band linac module finally accelerates the beam to the energy of ~ 50 MeV. Solenoid magnets downstream the gun provide transverse focusing.

In the following paragraphs, we describe an example of the simulations we performed for characterizing the performance of the VHF gun. The example shows a solution that (although not completely optimized and based on some simplifying assumptions) substantiates the possibility of an injector using the VHF gun to generate a beam with parameters in the range required for operating an ERL or a FEL.

The ASTRA [45] code was used to model the performance of the RF gun and APEX, and the parameters at

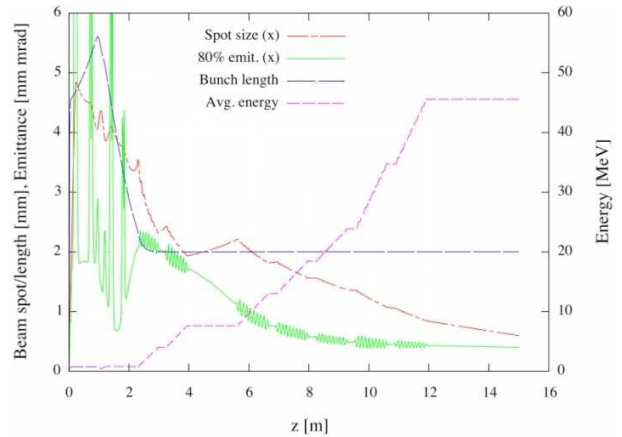


Figure 7:

the photocathode that were used as the input for the simulations are shown in Table 2. The thermal emittance of the emitted beam is taken to be very small to better study the effects of the space charge and the low frequency RF components on the evolution of beam quality in the photoinjector beamline.

The evolution of the main beam parameters is shown in Fig. 7, from the generation at the photocathode ($z = 0$ m) to beyond the exit of the second linac module ($z = 15$ m). At this point the beam has an average energy of slightly higher than 45 MeV and a bunch length (duration) of 2 mm (~ 6.7 ps r.m.s.). Emittance compensation has been carried out, with the final projected, normalized emittance of less than 0.5 mm mrad for 80% of the beam. The variation of the slice current and normalized emittance at the injector exit ($z = 15$ m) is shown in Fig. 8. After compression, the longitudinal profile takes on a skewed, pseudo-Gaussian distribution with a peak current of ~ 32 Amperes. The average value of the slice emittance (weighted by slice charge) is ~ 0.35 mm mrad.

Even if not completely optimized, the results from this example show the capability of the VHF gun to operate in a scheme and in a regime compatible with the operation of a 2-2.5 GeV linac-based VUV-soft x-ray FEL or ERL. In fact, normalized emittances and bunch charges are in the required ranges, and the bunch length at the exit of the injector is comparable with that requested for an ERL [8]. For the FEL case, in order to achieve the desired peak currents, a further compression downstream in the accelerator is necessary. Simulations with lower and higher charge per bunch have been also performed showing comparable results. Of course, the final design of an injector based on the VHF gun re-

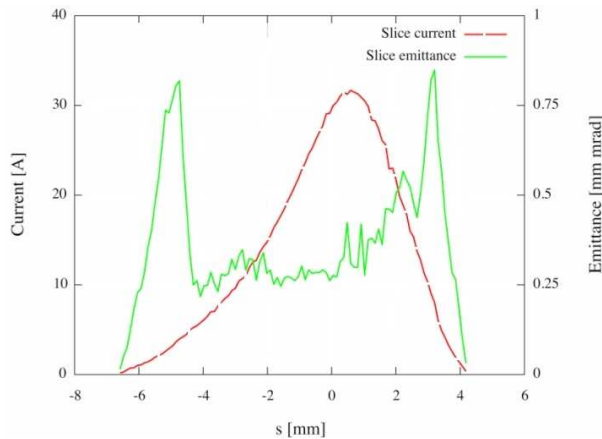


Figure 8:

quires simulations using a more realistic cathode thermal emittance (once the choice on the cathode type is finalized), and an accurate optimization of all the injector parameters similar to the one performed at Cornell for their DC gun-based injector [8].

The cathode choice and the related gun repetition rate are deeply connected to the available laser technology. Present pulsed fiber lasers are capable of ~ 200 W of average power in the infrared [46]. For example, a ~ 20 W average power laser can drive high quantum efficiency semiconductor cathodes directly (GaAs) or by higher harmonic conversion (CsTe) to generate nC bunches at 1 MHz repetition rate. A 200 W laser after higher harmonic conversion, could be used instead for operating with low quantum efficiency metal cathodes (Cu and Mg for example) to ~ 100 kHz repetition rates with nC bunches. Considerably higher repetition rates can be obtained if the charge per bunch is reduced.

We have also performed initial optimization studies of some of the VHF gun parameters. In particular, we were interested in studying the effects on the beam quality at the injector high-energy exit due to variations in the geometry of the electrodes that comprise the accelerating gap, and to variations of the cavity resonant frequency [21]. The simulations showed that for high charge bunches, the overall beam quality after longitudinal compression and emittance compensation can be remarkably insensitive to the details of the gap geometry. In this situation, a flat cathode with maximum accelerating gradient is thus favored over more complicated geometries. Additional studies are required for understanding the effects of the cathode area geometry in the low charge (hundred pC) regime.

Simulations also showed that beam dynamics and

beamline optimization are marginally affected by RF gun frequency variation over a broad band (from 50 to 200 MHz). This allowed us to define the resonant frequency for the gun based only on RF and mechanical considerations. The 106 MHz is one of the possible choices trading between a lower power density on the cavity walls (for an easy cooling of the structure) and a reasonably high voltage breakdown limit, between a practical size and sufficiently large apertures for an efficient pumping system, between cost of the cavity and cost of the RF power source [47]. We are also evaluating and designing 200 MHz and 352 MHz versions of the cavity in order to compare these different tradeoffs within the VHF bandwidth.

4. Conclusions

In summary, we have presented the concepts and the preliminary design results for a high brightness CW normal-conducting RF gun operating in the VHF frequency range. Beam dynamics simulations showed that the quality of the beam generated by such a source is suitable for ERL and high average power FEL applications. The simple and reliable scheme based on mature RF and mechanical technology makes the VHF gun an appealing alternative to DC and super-conducting electron guns when high repetition rates are required.

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Figure 1. 3-D CAD model of the normal conducting VHF cavity for a high repetition rate photoinjector. Slots around the periphery allow for vacuum pumps located in the antechamber. (In color online)

Figure 2. Possible multipactoring modes vs. accelerating gradient for the VHF structure. Fishpact calculation. (In color online)

Figure 3. Cathode area detail. (In color online)

Figure 4. Logarithm of the magnitude of the electric field in the outer pump slot region of cavity. (In color online)

Figure 5. Temperature distribution on the cavity calculated at the nominal power. (In color online)

Figure 6. The Advanced Photoinjector EXperiment (APEX) schematic layout. APEX was used as a bench test for simulating the performance of VHF gun described in this paper. (In color online)

Figure 7. Example of beam quality versus the longitudinal position along APEX. (In color online)

Figure 8. Example of beam longitudinal distribution and slice emittance at the exit of APEX. (In color online)

Parameter	Value	Units
Mechanical:		
Cavity radius	56	cm
Total length	58	cm
Accelerating gap	4	cm
Max gap deformation (combined thermal and pressure load)	0.17	mm
Max von-Mises stress	< 156	MPa
Peak temperature rise	83	°C
Electrical:		
Frequency	106	MHz
Q_0	37800	
Repetition Rate	CW	
Gap Voltage	750	kV
Field at cathode	20	MV/m
Peak surface field	26	MV/m
RF power for 750 kV	73	kW
Peak wall power density	8	W/cm ²
Stored energy	4.1	J
Vacuum:		
Pressure	8.5×10^{-11}	Torr
Number of vacuum pumping slots	36	
Number of getter pump modules	36	
Multipacting-free operating field	14-21	MV/m

Table 1: VHF gun nominal values for the main parameters

Bunch charge	500	pC
Long. distribution	Flat top	
Bunch Length (FWHM)	75	ps
r.m.s. energy spread	0.1	eV
Transv. distribution	Parabolic	
Spot size (r.m.s.)	0.5	mm
Thermal emittance	0.05	mm-mrad

Table 2: Beam parameters at the cathode used in the simulation