SLAC-PUB-16407

CLIC Drive Beam Gun

A.D. Yeremian, A. Jensen, E. Jongewaard, J. Neilson

September 22, 2015

Introduction:

The Compact Linear Collider (CLIC) is a proposed future electron-positron collider, designed to perform collisions at energies from 0.5 to 5 TeV, with a nominal design optimized for 3 TeV (Dannheim, 2012). CLIC generates three beams: the drive beam, the main electron beam and the positron beam. The drive beam is a high current electron beam that is accelerated in an S-band linac and then decelerated in 12 GHz structures to generate the RF for accelerating the colliding main electron and positron beams. The drive beam employs a high current thermionic DC electron gun. This report explores the optimal anode – cathode geometry as well as analyzes the mechanical and electrical integrity of the gun structure designed by CERN.

Drive Beam Electron Gun Requirements:

The Drive Beam Accelerator consists of a thermionic DC gun, bunching section and an accelerating section. The average current at the decelerating structures needs to be approximately 4 A, and at the end of the injector 4.2 A. Taking into account expected current loss in the bunching section, the gun needs to produce 5 to 6.6 A (~85% to 65% transmission to the end of the injector respectively). Based on the successful operation of the CLIC Test Facility 3 (CTF3) injector, a 140 keV thermionic gun is envisioned. The gun requirements are in table 1 and a visual representation of the pulse structure is in Figure 1.

Table 1. CLIC Thermionic Gun Requirements

Parameter	Nominal value	Unit
Beam Energy	100-150 (140 nominal)	keV
Pulse Length	140.3	μs
Beam current	5 – 6.6	A
Bunch spacing/Freq.	2/500	ns, MHz
Emittance, N, edge	<25	π-mm-mrad
Repetition rate	50	Hz
Beam radius at gun exit	< 10	mm
Vacuum	10^{-9}	mbar

SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-76SF00515 and CERN.

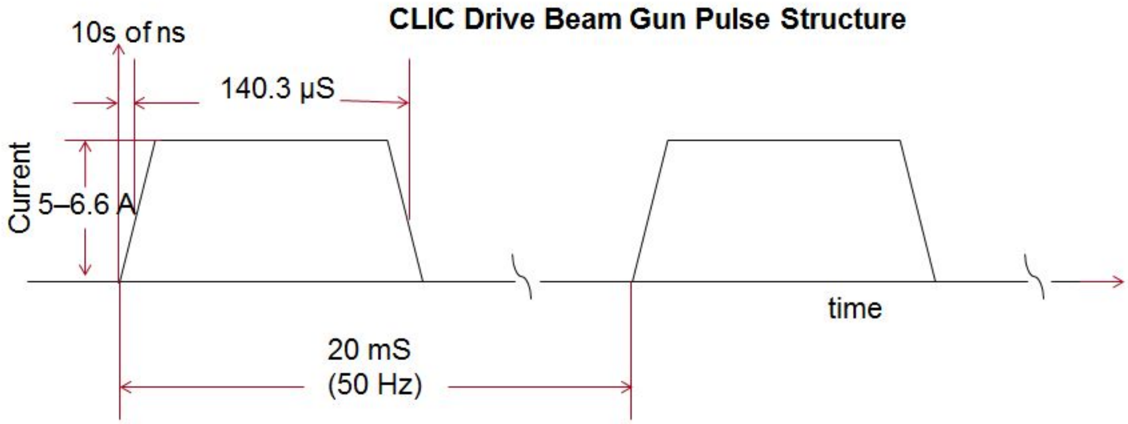

Figure 1. CLIC Drive Beam Gun Pulse Structure

Cathode and Anode Geometry:

The CLIC Drive Beam gun design employs a grid pulsed cathode to form the pulse train at the gun. Due to the high average current and relatively large power dissipated on the grid, CPI's YU156 3 cm^2 cathode is used. Table 2 shows the specifications of this cathode. However the actual area of the cathode is slightly larger than indicated in the table.

Table 2. CPI YU 156 cathode specifications indicated by the red arrow.

TYPE NUMBER	Cooling[1]	FILAMENT Volts	FILAMENT Amps	CATHODE Area, sq. cm.	CATHODE Type[2]	CONFLAT Size, in.	D_{GK}, microns	MAXIMUM RATINGS E_f, V	MAXIMUM RATINGS E_c, Vdc	MAXIMUM RATINGS I_c, mAdc	EMISSION E_b, Vdc	EMISSION Ib, Amps
Y-809	A/CC	6.0	1.3	0.1	D	2 3/4	135	6.3	-150	50	6.0	0.003
YU-180	A/CC	6.0	1.3	0.1	D	2 3/4	150	6.6	-150	50	150	0.25
Y-646B	A/CC	6.0	1.4	0.5	D	N/A	150	6.3	-150	50	150	0.75
Y-845	A/CC	6.0	1.4	0.5	D	2 3/4	140	7.5	-150	25	100	1.25
Y-646E	A/CC	6.3	2.2	1.0	D	N/A	150	6.6	-200	75	100	3
YU-171	A/CC	6.3	2.2	1.0	D	2 3/4	160	7.5	-150	25	100	3
Y-646	A/CC	6.3	1.3	0.8	O	N/A	150	6.6	-150	45	180	10
Y-796	A/CC	6.0	5.8	2.0	D	3 3/8	170	7.5	-150	50	100	12
Y-824	A/CC	6.0	5.8	2.0	D	2 3/4	190	7.5	-150	50	200	15
YU-156	A/CC	6.0	8.3	3.0	D	3 3/8	170	7.5	-150	550	100	18

[1] All gun assemblies are forced air and conduction cooled

[2] O = Oxide Cathode, D = Dispenser Cathode

The cathode focus electrode and anode geometry is approximately a Pierce-gun geometry similar to the SLAC thermionic gun (Koontz and Miller, 1975) but optimized for CLIC and is shown in figure 2.

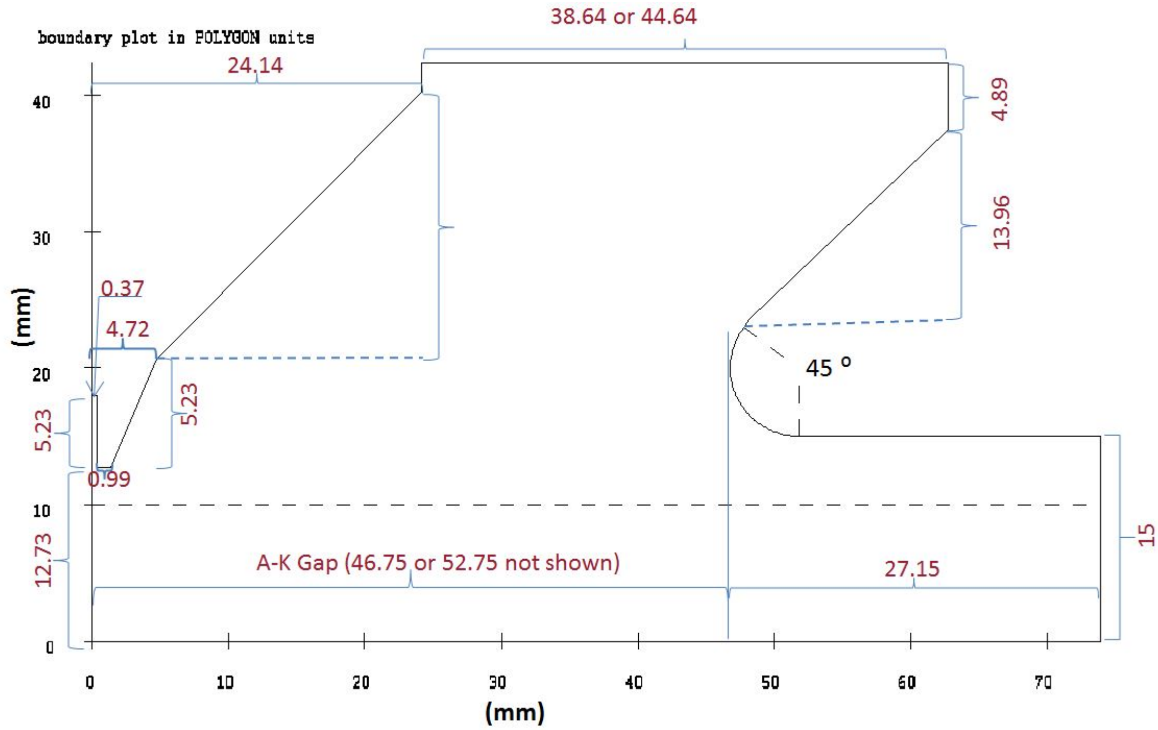

Figure 2. CLIC gun electrode geometry for the SLAC optimized cases.

Gun Simulations

The cathode anode region of the gun was simulated using two different, well proven simulation codes: MICHELLE, a 3D finite-element gun and collector modeling code (Petillo, 2001) and EGUN (Herrmannsfeldt, 1988), a 2D gun simulation code. Both codes compute trajectories of charged particles in electrostatic and magnetostatic fields, including the effects of space charge and self-magnetic fields

MICHELLE simulations of the gun were done with the grid in both 2D (modeled as axisymmetric ring) and 3D (modeled as 10 degree wedge). The grid dimensions used in the simulation were obtained from the cathode manufacturer and the grid geometry for the 2d and 3d case is shown in Figure 3. The simulated current emission in the 5 to 6.6 A range required from the CLIC drive beam gun was similar for both cases, with less than a 10% difference. Using MICHELLE we also simulated the effect on current emission due to grid movement ±0.08 mm from the nominal position from the cathode face. Figure 4 shows the results of comparing 2D and 3D calculations on current emission with variation in the grid distance from the cathode.

The space charge limited case was calculated for the CERN electrode design using both codes without the grid. The results were quite close for the space charge limited case, with MICHELLE producing a beam of 18 A with a geometric edge emittance of 31 π-mm-mrad and EGUN producing 18 A with geometric emittance of 32 π-mm-mrad (cathode thermal emittance not included). We were unable to run a comparison of the grid case with EGUN due to excessive run time required to perform properly converged EGUN simulations with the very fine mesh necessary to model the grid.

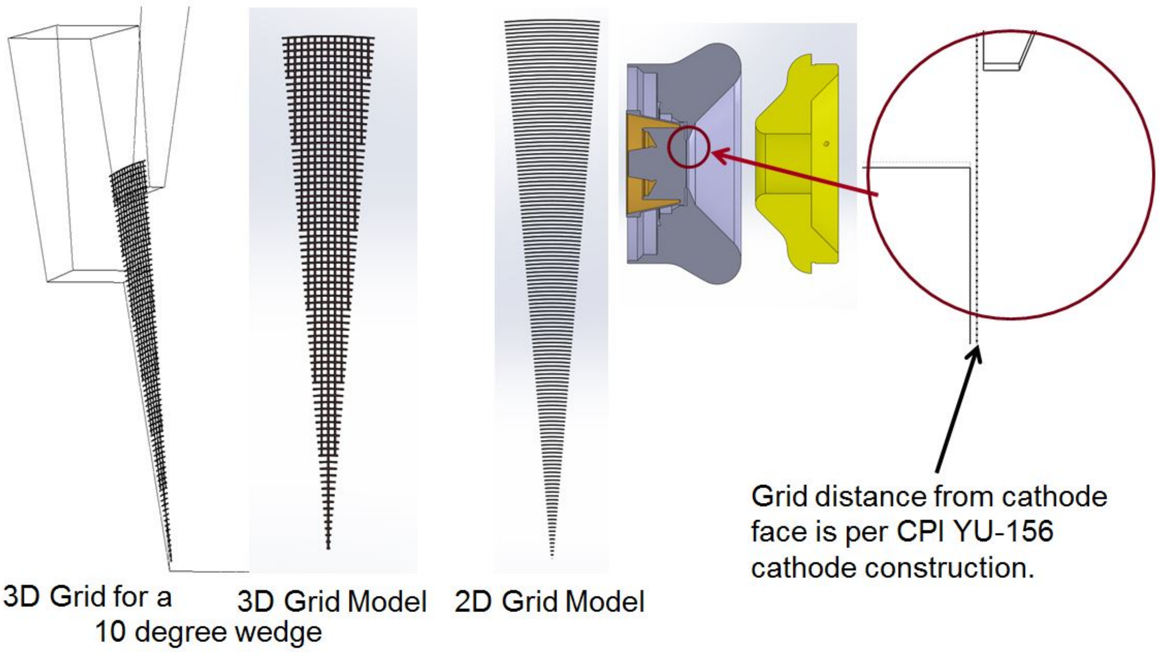

Figure 3. CLIC gun cathode grid geometry as simulated in MICHELLE according to the grid dimensions obtained from CPI.

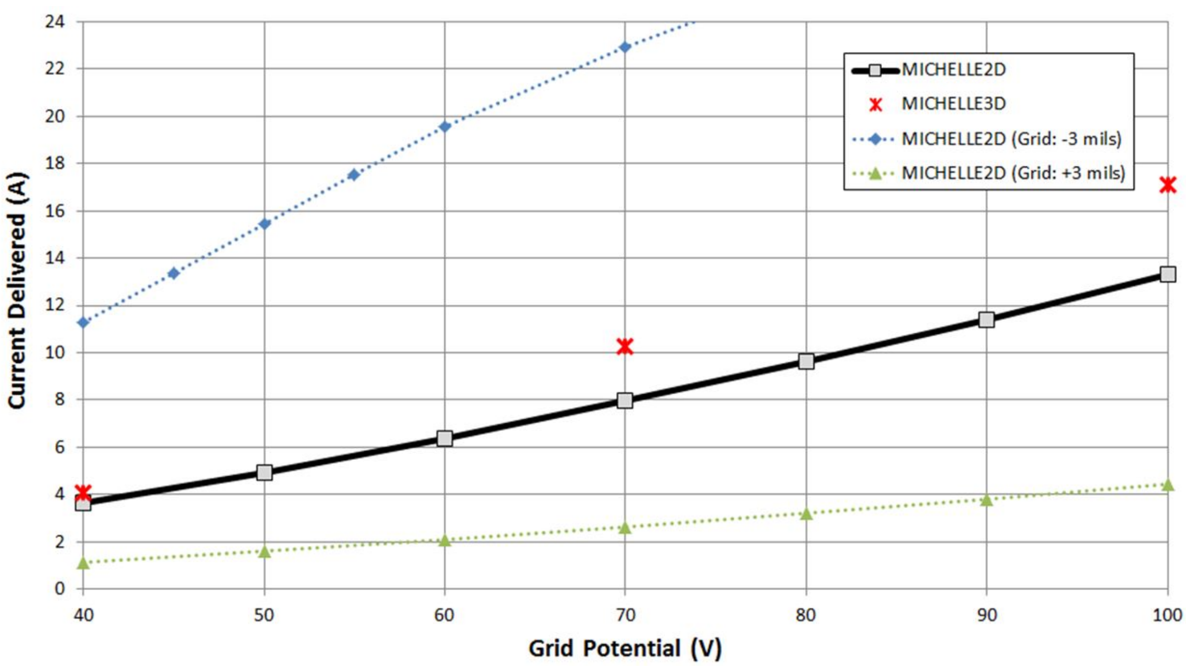

Figure 4. MICHELLE simulations including the grid in 2D and 3D as well as cathode to grid variance of ±0.08 mm.

The grid has a significant effect on the beam performance. It helps to reduse the beam waist and angular deviation of the edge emitted rays, on the other hand the grid mesh has a defocusing effect on the electrons going through it. In Figure 5 we show simulations of the gun performance to observe the effect of the grid presence on the ray trajectories. For this comparison we ran four cases:

- EGUN and MICHELLE without grid and space charge limited current
- MICHELLE with grid and current set to 12.5 A using grid bias
- EGUN without grid and current fixed at 12.5 A using code run time parameter AMPS

The EGUN/ MICHELLE case without grid and space charge limited flow of 18 amps had very similar trajectories (Figs. 5a and b) with both showing significant deviation in emission angle from the cathode edge compared to the inner rays' emission angles. When the current is reduced to 12.5 amps in the EGUN calculation using the AMPS parameter (Fig. 5c) the trajectories' emission angles are largely unaffected and there is only minimal effect on the beam waist. For the MICHELLE case with 12.5 amp grid limited current (Fig. 5d) there is a significant reduction in beam waist and angular deviation of the edge emitted rays.

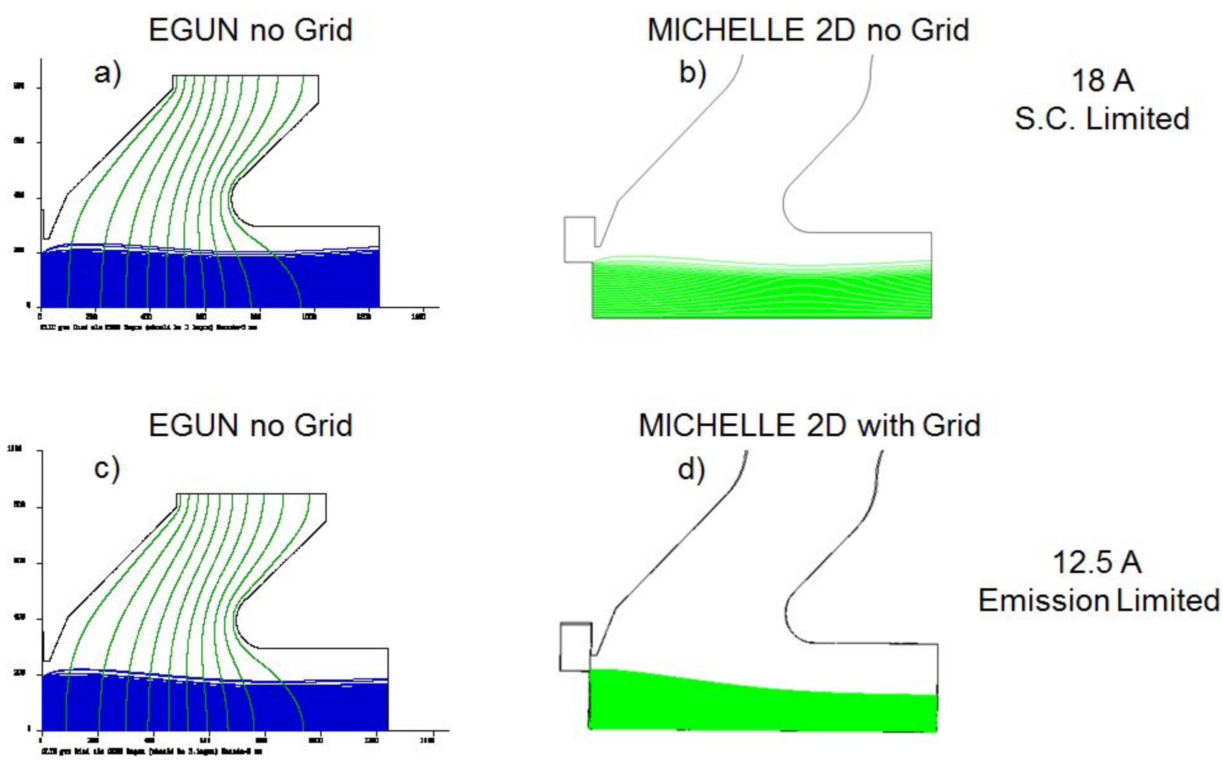

Figure 5 **EGUN Diode and MICHELLE 2D with and without grid ray trace comparison for the geometry received from CERN (A-K gap 3.5 cm), a) and b) EGUN and MICHELLE no grid Space charge limited flow, c) EGUN for space emission limited with the AMPS parameter, d) MICHELLE 2D for emission limited with the grid.**

Figure 6 shows the emittance vs. delivered current plot for Michele 2D with grid. The values calculated with EGUN without grid are designated on the same graph. In MICHELLE delivered current means the current emitted from the cathode minus the current intercepted by the grid, while in EGUN it means limiting the current using the code parameter AMPS. One can see that in the case of the geometry received from CERN (3.5 mm A-K gap, 18 A space charge limited) and limiting the current to 12.5 A, where the grid potential is closer to the space charge limited equipotential voltage and hence the defocusing effects of individual meshes in the grid are relatively small, the no-grid EGUN emittance is larger than that calculated by MICHELE 2D with grid. This is likely due to the emittance being dominated by the outer rays not being gathered in EGUN without grid as they are by the grid in MICHELLE 2D. On the other hand for the 5 amp case the individual grid mesh focusing is significant enough to overtake improvement of the emittance due to gathering the rays in the radial direction and the emittance calculated by MICHELLE 2D is larger than the emittance calculated by EGUN. However, when the A-K gap is increased so that at 5 to 6.6 A the gun is running closer to the space charge limited condition, the emittance calculated with EGUN with no grid is very close to the emittance calculated by MICHELLE 2D with grid.

When the potential is the same as the equipotential line at the grid location for the space charge limited case without the grid, then the grid is electrically transparent and has practically no effect, however when the current is limited severely using the grid, the grid defocusing can have significant adverse effect on the beam emittance. On the other hand including the grid does gather the outer rays into the fold better and this can result in slight improvement in the emittance at or near the space charge limited regime. Depending on how far below the space charge limited case the gun runs, one effect can dominate the other. In either case, the simulations suggest it is better to run the gun close to its space charge limited flow, meaning the anode-cathode gap should be chosen such that there is a little bit of head room above the required current but not too much if minimizing the emittance is an important consideration. When the grid is used to severely reduce the current for a gun with a given anode-cathode geometry, the defocusing effects of the grid can have deleterious effect on the beam emittance.

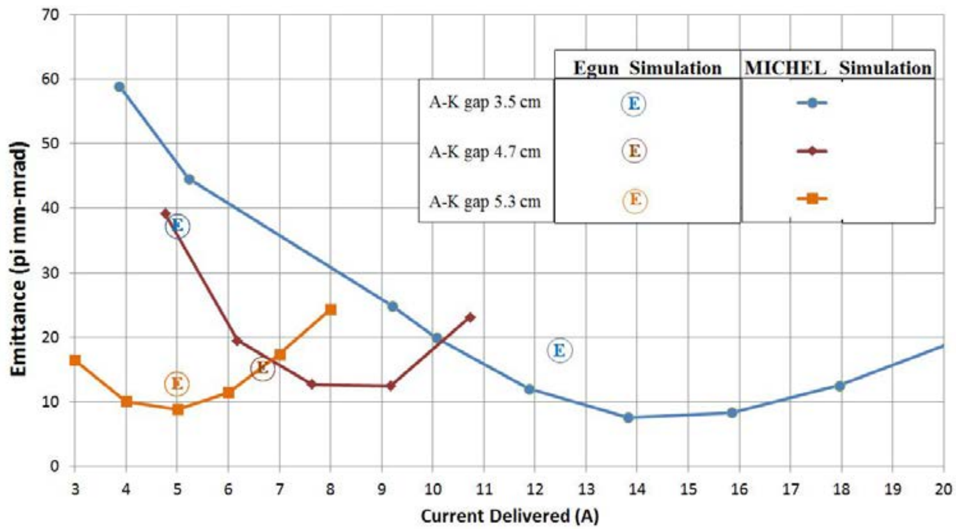

Figure 6. EGUN Diode and MICHELLE 2D with Grid simulation of emittance vs current for 3 cases: A-K Gap =3.5 cm geometry received from CERN, and A-K gap = 4.675 cm and 5.275 cm which would provide enough current headroom while still meeting the emittance requirements at the operating range of 5 to 6.6 A.

Figure 7 shows the beam radius vs current relationship for the three cases as simulated by MICHELLE 2D with grid and EGUN diode with current limited using the AMPS parameter. In all cases at the operating range of 5 to 6.6 amps the radius was less than the 10 mm minimum permitted value. In the A-K Gap 3.5 cm case (CERN geometry), the radius is smaller in the lower current cases; the larger emittance (see Fig. 6) is dominated by the angular component of the beam transverse phase space.

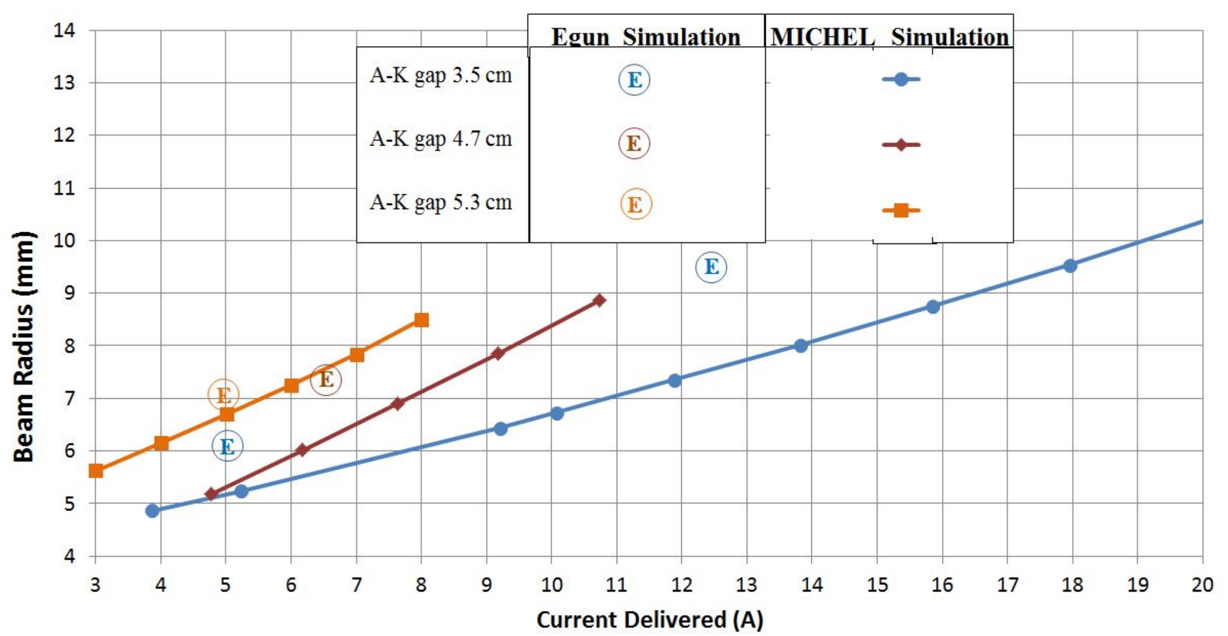

Figure 7. EGUN Diode and MICHELLE 2D with grid simulation of radius at the gun exit vs current for three cases: A-K Gap =3.5 cm geometry received from CERN, A-K gap = 4.675 and 5.275 cm.

Figure 8 shows the grid voltage needed to achieve the delivered current as simulated by MICHELLE 2D. MICHELLE also provides the current intercepted by the grid and the values for the nominal delivered current range are shown on the figure. In all cases the power dissipated on the grid is well below the maximum allowed 4 W. The dissipated power is equal to the current intercepted by the grid times the voltage on the grid.

The results of MICHELLE and EGUN calculations for surface electric field on the anode tip are shown in Figure 9. MICHELLE 2D and 3D simulations show a maximum electric field of 132 kV/cm on the anode tip for the geometry provided by CERN (A-K gap 3.5 cm), while EGUN calculates 123 kV/cm, about 7% lower than MICHELLE. EGUN simulations for the A-K gap of 4.625 cm and 5.275 cm show a maximum electric field of 87 kV/cm and 72 kV/cm respectively. The latter two surface field values are well within expected reliable operation range while the electric field for the A-K gap 3.5 cm case is near the edge of normal operating gradients. This threshold for the anode electrode is approximately 110 kV/cm based on operation of similar guns. The threshold on the maximum electric field on the cathode focus electrode is lower than on the anode, since the focus electrode is hot and at high voltage. Guns at SLAC are designed to keep the electric field on the cathode below 75 kV/cm. As can be seen on Figure 9, the electric field on the cathode for the A-K gap of 3.5 cm case is about 100 kV/cm but for the A-K gap of 4.675 cm and 5.275 cm cases it is only 65 kV/cm and 55 kV/cm respectively.

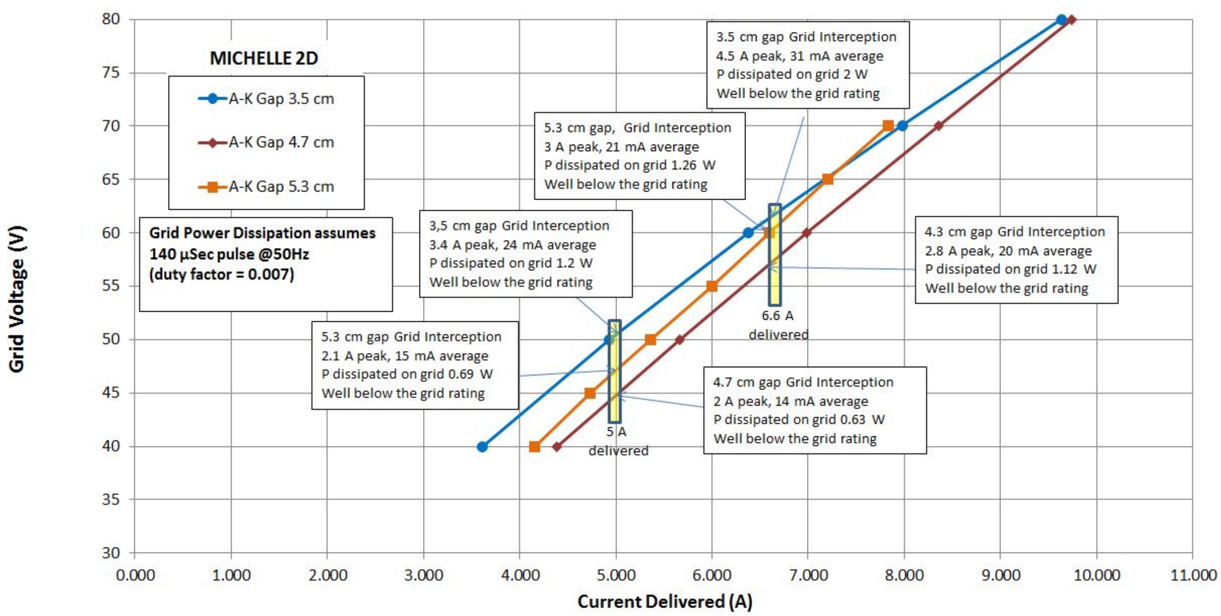

Figure 8. MICHELLE 2D with Grid simulation of grid voltage vs current delivered for 3 cases: A-K Gap =3.5 cm geometry received from CERN, A-K gap = 4.675 and 5.275 cm.

Surface Electric Field (kV/cm)

A-K Gap (cm)	Focus Electrode MICHELLE 2D and 3D	Focus Electrode EGUN	Anode Tip MICHELLE 2D and 3D	Anode Tip EGUN
3.5	---	65	132	123
4.7			---	87
5.3	---	55	---	72

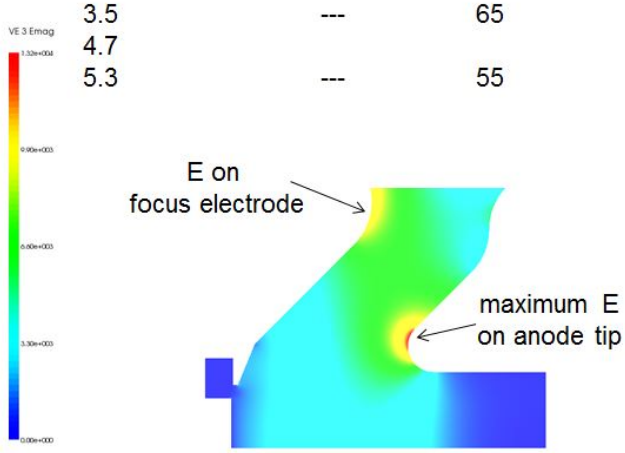

Figure 9. EGUN Diode and MICHELLE 2D with Grid simulation of surface electric field for 3 cases: A-K Gap =3.5 cm geometry received from CERN, A-K gap = 4.675 cm and 5.275 cm.

Review of CERN's Mechanical Gun Design

We have reviewed the proposed mechanical design and assembly for the CERN CLIC drive beam gun and offer the following comments and suggestions:

In general the proposed assembly and alignment technique seems adequate for the desired alignment requirements. CERN is proposing bolting up several assemblies of reasonable precision, measuring the cathode position relative to the anode support mating features and adjusting the anode position to place it in the desired location. As noted in CERN's description of the process, it may be painful, but only needs to be done once. We agree and have certainly made precision assemblies using similar techniques in the past.

To make future rework less problematic CERN might consider adding alignment features to the conflat flange interfaces so if they need to be taken apart subsequent re-assembly can be performed without having to repeat the entire alignment and fiducialization process. This can be as simple as machining the OD of the flanges to a precise dimension and using a fixture ring to hold the flanges concentric on initial assembly. Another possibility might be the addition of alignment pins to each conflat interface; this can be accomplished by match drilling mating flange pairs prior to final assembly (see Figure 10).

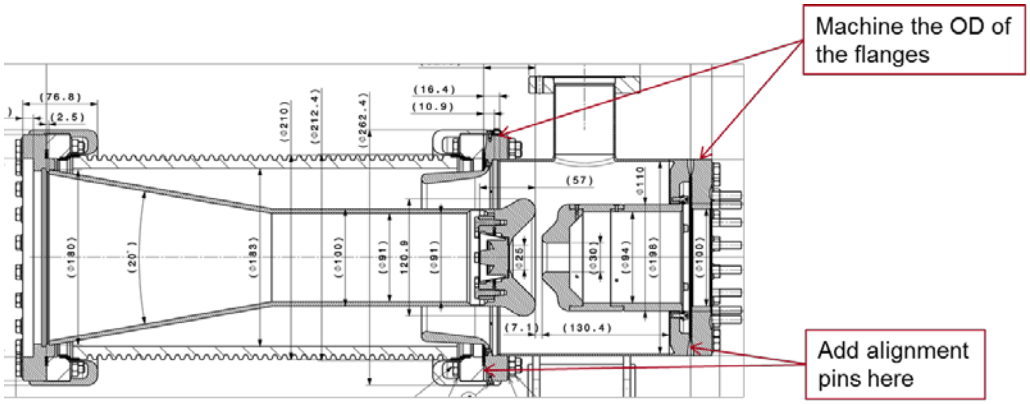

Figure 10: Detail from CERN drawing CLINFTLA0004

We recommend implifying the anode support design to a single cylinder with flanges at both ends. The end of the cylinder towards the anode has an internal flange and the down beam end has an external flange. The flange diameters and overall length can be oversize and machined at the final assembly stage to compensate for the assembly stack up and place the anode precisely where needed. This will also allow changing the fasteners from radially oriented flat head screws to axially oriented screws to eliminate the potential to misalign the anode when the fasteners are tightened (see Figure 11).

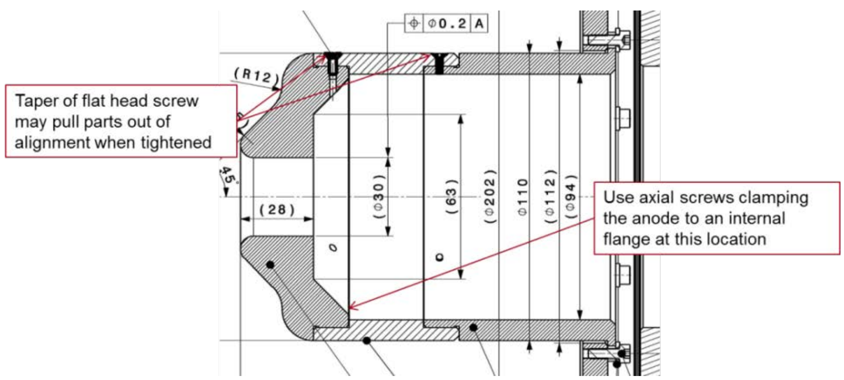

Figure 11: Detail from CERN drawing CLINFTLA0005

As mentioned above, the maximum electric field threshold on the cathode focus electrode is lower than that for the anode and in the design we received from CERN (A-k gap 3.5 cm) the field on the cathode electrode exceeds the 75 kV/cm empirical comfort level. The geometries offered by SLAC are both comfortably below this level. Additionally the recommendations below further mitigate the risk factors.

In addition to the proposed polishing of the focus electrode and stem we also recommend using a low inclusion content alloy for the focus electrode such as type 317L VAR stainless steel. This can help in situations such as this where the HV gradients are high.

We recommend using studs and nuts rather than screws to fix the cathode CF flange to the back of the focus electrode to protect the expensive gun stem/focus electrode assembly from damage from seized hardware (see Figure 12).

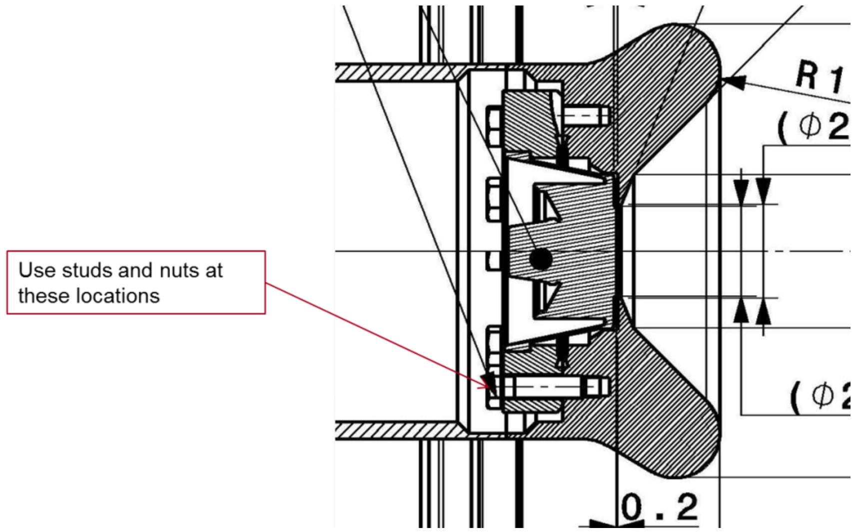

Figure 12: Detail from CERN drawing CLINFTLA0015

While we don’t always follow this guidance ourselves, try to limit conflat flange firing temperatures in the 650 °C to 750 °C range to prevent excessive softening of the knife edges

We recommend vening all close fit mechanical interfaces in the vacuum space to reduce the possibility of virtual leaks, in particular the vacuum side of the CF gaskets on the HV isolator flanges (see Figure 13)

We, also recommend considering the possibility of altering the anode vacuum can to flange joint (see Figure 14) to eliminate the thin vacuum wall at the end of the blind threaded hole. This might be accomplished by stepping down to a smaller tube which would also allow use of through bolts on that flange and. This should provide better reliability through repeated mating cycles.

.

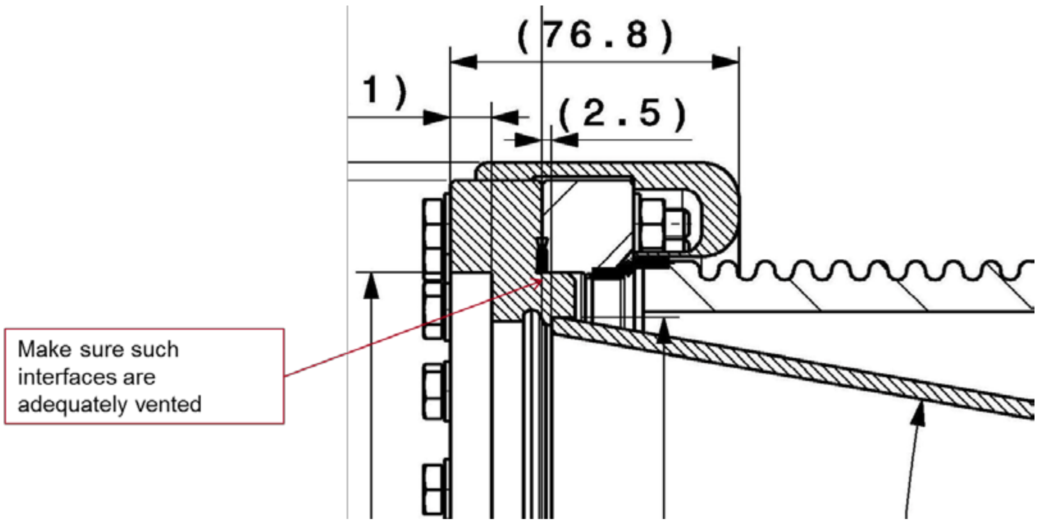

Figure 13: Detail from CERN drawing CLINFTLA0004

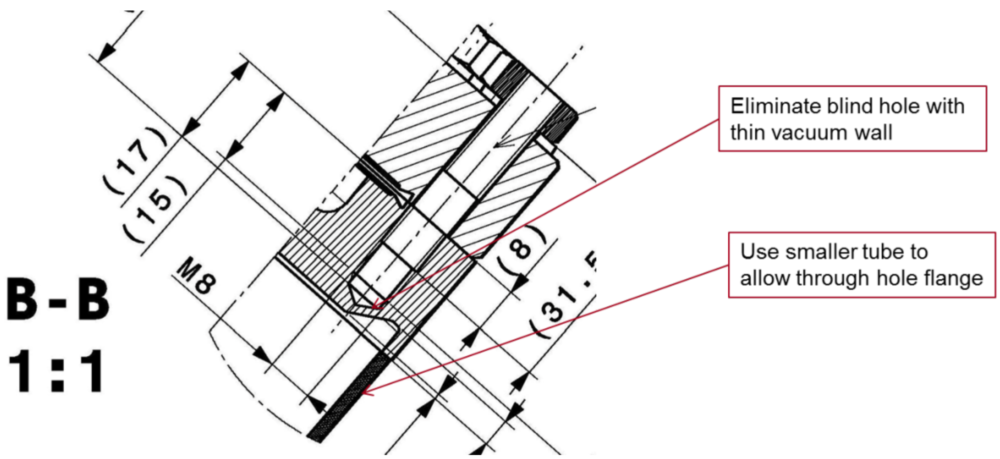

Figure 14: Detail from CERN drawing CLINFTLA0005

Summary:

A thermionic electron gun with anode-cathode gap geometry similar to the SLAC guns, with a CPI model YU-156 3 cm^2 gridded cathode running at 140 kV A-K gap voltage, meets the CLIC Drive beam requirements. We recommend the 4.7 cm A-K gap in order to provide plenty of current headroom while comfortably meeting the emittance requirements and operating in a comfortable range of the grid voltage and maximum allowable electric field on the cathode focus electrode and the anode tip. The overall mechanical design of the gun body is reasonable. We have made some recommendations based on our experience to increase reliability and reduce risk.

Acknowledgements:
We thank Andrew Haase for consultations about the electron gun mechanical design and to William Herrmannsfeldt for consultation on the intricacies of the EGUN code as applicable to the CLIC gun design.

References:

Dannheim D., "CLIC e+e- Linear Collider Studies", Physics.Acc-ph, arXiv:1208.1402v1, 2012
Herrmannsfeldt W.B., "EGUN, an Electron Optics and Gun Design Program", SLAC PUB 331, Stanford , CA, 1988.

Koontz R.F., Miller R.H., "Nanosecond Electron Beam Generation and Instrumentation at SLAC", IEEE proceedings on Nuclear Science, Vol. 22 no. 3, June 1975, p1350

Petillo J., et. al., "The MICHELLE Electron Gun and Collector Modeling Tool", Proceedings of the Particle Accelerator Conference PAC2001, Chicago, IL, (June 18-22, 2001), pp. 3054 – 3056