I. Introduction
The electron beam requirements for a linac based VUV FEL, such as the WiFEL, are very stringent. The linac will be required to produce 1 mA of average current at a multi-megahertz pulse repetition frequency, with less than 1 mm-mrad normalized transverse slice emittance. The FEL interaction requires peak currents in the kilo-ampere range to operate and limitations on the allowed residual correlated energy spread and microbunching sensitivities limits the compression ratio to ~20, thus the peak bunch current out of the injector is set at ~50 amps.

The other problem facing the injector is microbunching in the compressors. The longitudinal bunch profile must be optimized to avoid ‘Horns’ at the front and rear of the bunch charge density profile[6]. It also needs to have less than 10^{-4} coherent energy modulations along the bunch going into the compressor or sufficient uncorrelated energy spread to prevent CSR or resistive wakefield microbunching. Presently the best means of temporally shaping the pulse is splitting it up and performing superposition of the pieces[1,3] and using this technique it will be very difficult to produce a pulse with less than 0.01% temporal modulation. This forces the WiFEL injector to use “blow out” mode bunches which have a uniform charge density to suppress the non-linear space charge forces in compressors[3]. These bunches are produced by a photocathode using a laser pulse of about 30 fs duration with a hemispherical transverse density distribution. The “charge pancake” produced by the laser pulse expands under space charge forces to an ellipsoidal bunch with constant charge density[2].

The limit on the “blow-out” mode bunch approach is that the charge density of the bunch is only dependent on the electric field applied to the cathode. For a greater peak bunch current, either the field must be increased or the radius of the bunch must be enlarged. The limit on the emission radius is set by the transverse emittance; at 1 mm rms radius, the thermal emittance for Cs₂Te reaches about 1 mm-mrad[5]; the radius of the bunch cannot be larger than this and stay within the specification for the FEL. If a limit of 0.8 mm sigma on the cathode spot is observed, then the electric field on the cathode necessary to achieve 50 amp peak is about 37 MV/m[4]. Such a CW field is too great for either a DC gun (field emission) or a CW normal conducting rf gun (thermal load), but is well within the reach of an SRF electron gun. For this reason, an SRF gun optimized to produce a large field on the cathode is the only viable option for a seeded FEL.

Section 2 describes the selection process for the type of rf structure. Section 3 describes the Superfish cavity modeling. Section 4 describes the ASTRA particle code simulations. Section 5 describes the results.

II. The Superconducting Rf Structure
An SRF electron gun is necessary to provide the high quality, high peak current beam for a seeded FEL. The SRF gun designs presently available revolve around elliptical cavities with an initial half cell which is run significantly off crest to compensate for energy spread caused by space charge. For this application, however, the half wave resonator structure [12], Fig 1, was selected for the SRF electron gun because, potentially, it has much better beam properties than a conventional elliptical cavity. It has the advantage of a very flat field profile in the accelerating gap, almost like a DC gun, which introduces less than 15% of the rf curvature on the bunch energy profile that a Tesla cavity based device does. It also is relatively (+/- 4.2 ps) insensitive to errors in the drive laser timing with respect to the cavity rf compared to a higher frequency cavity. Finally it has about half the magnetic field per MV/m of field[9], so if field emission limitations can be
overcome, peak electric fields could be up to twice that of elliptical cavities, resulting in higher peak bunch currents and higher gun exit energies. Operationally, the design is attractive because it operates at 4 K with lower circulating rf currents in the cathode region making a load lock and rf choke much simpler. Superconducting solenoids have already been integrated into these cavities [8], potentially improving the emittance compensation of the gun. Superfish [13] and ASTRA [7] were used to simulate beam properties of the gun design in Figure 1 using “blow-out” mode bunches when propagated beyond the first full Tesla style cryomodule. Both the Superfish and Astra decks are attached in Appendix 1. Further optimization should improve the projected beam performance.

The problems for the half-wave cavity are the same as with all photocathode srf guns – only one has been built that worked and it was nowhere near the parameter space we need to operate in for the WiFEL. The most mature designs available use elliptical TESLA cavity technology [9,10], but none of those have produced a beam yet. That leaves questions about cavity Q degradation due to cathode material migration and maximum E field limitations open for all high current srf electron guns.

III. Cavity Design

The superconducting quarter wave resonator structure has been in use more than three decades [11]. These devices typically operate in the range of 100 to 400 MHz with a beta of much less than 1. The cavities operate at 4 K rather than 2 K because the BCS losses go as the frequency squared and lower temperatures are unnecessary for normal operation. Our cavities were modeled using SUPERFISH. This program solves for the fields in a cylindrically symmetric model of a cavity. W. Graves performed scaling studies of the frequency versus peak fields for a quarter-wave structure [7]. He determined that 200 MHz was close to the optimal frequency for that shape and that the original design could be improved by tapering the central post which stiffened it against microphonic vibrations and reduced the peak electric field at the edges. For this reason, I have been designing around a 200 MHz cavity. None of the models presented in this note include couplers or non-superconducting cathodes which might significantly effect the Q of the structures. The models do provide a means to generate an electric field map along the Z axis for a particular cavity shape and a value for the ratio of peak magnetic field versus peak electric field in the cavity, which is one of the principle limiting factors on the accelerating gradient of the cavity. One of the other problems that shows up in designing a half wave gun cavity is that it is desirable to achieve the largest kinetic energy out of the gun to slow the effects of longitudinal space charge effects on the beam. If the beam is at too low an energy at the exit of the gun cavity, the space charge forces lengthen the bunch in the solenoid/drift region prior to the first cryomodule in which emittance compensation is done. This lowers the peak bunch current potentially making it unusable with the specified bunch compressor.
system. To achieve a high final kinetic energy from the gun either the gap in the cavity must be lengthened to increase the total integrated gradient or multiple cavities need to be implemented. To assert a second cavity of the quarter wave style requires either a long drift between the gaps of two adjacent cavities or a nested cavity structure. Figure 2. Since a long drift at low kinetic energy is the problem we’re putting two cavities together to avoid, that solution doesn’t work. Nesting two cavities around each other might work but would make the design very difficult to manufacture and could potentially make the structure difficult to stiffen and cool. The other option is to simply make the gap much wider, as in Fig 1. The problem with this is the field profile invariably sags between the two posts as the gap widens. Terry Grimm from Niowave [12] explained the basic principles on how to flatten the field profile as increasing the radii of the inner posts to make the field more uniform between them and then increasing the radius of the outer wall to increase the cavity’s stored energy and then finally adjusting the length of the resonator to set the resonant frequency. I followed this procedure in designing the cavity in Figure 1, but I added a Pierce geometry to the cathode post to add some focusing to the beam and further smooth the field profile in the gap. The cavity has a ratio of about 1 mT / MV/m and the peak electric field is about 1.5 times the value along the z axis. The gap was scaled to provide about 4 MeV kinetic energy gain for a peak cavity field of 60 MV/m, giving a peak on axis field of 40 MV/m. Further optimization of this cavity to improve the field flatness, reduce the ratio of the peak E field to field on the z axis, or reduce the tuning sensitivity should be done prior to cutting metal.

**IV. ASTRA Model**

Astra is a particle tracking code written by K. Flottmann at DESY. It has been modified to perform simulations of blow-out mode bunch formation at DESY using a multigrid solver[19]. The code automatically updates the mesh size as the simulation progresses. This coupled with the fact it is really a 2D code gives it about an order of magnitude speed advantage over PARMELA[18] making it very attractive for testing new field maps and scanning parameter spaces for a particular solution.

The generation of the initial charge pancake distribution is described elsewhere[20]. The gun cavity phase is determined by balancing the bunch energy spread, transverse emittance and kinetic energy at the exit against the electric field needed to keep the peak bunch current well above 50 A, Figure 3. For these simulations, I selected 260 degrees
since this gives the maximum peak current from the gun and close to the maximum kinetic energy. The particle distribution produced at the end of the cavity for this simulation is then taken and set as the input for the emittance solenoid compensation scans. This distribution has a +/-50 keV chirp across the bunch due to the space charge. In an L band gun this is compensated for by phasing the gun cavity so the rf induced energy spread bucks the space charge energy spread, but in a DC or low frequency gun the bunch subtends too small an angle to be easily effected by the rf waveform. This is good; trying to correct the linear space charge term with the rf cosine term before emittance compensation will cause higher order energy modulations across the bunch which may become a problem at the compressor, but it’s bad since it makes emittance compensation more difficult. The standard compensation solution used [23], assumes that the beam’s sigma prime is much less than 1 and the beam has a narrow energy spread. Neither of these assumptions is valid in this case. Therefore, the solenoid strength and position of the first cryomodule must be adjusted to accelerate the bunch before the peak current drops while maintaining a reasonable emittance envelope.

The gun is emittance compensated using the technique described in [23] using a solenoid placed after the gun focusing the beam to a waist at the entrance to the first cryomodule. This solenoid should be placed as close as possible to the cathode to minimize the dilution of the original emittance, in this case the centerline of the solenoid has been placed at a point where the field along the z axis is less than 1e-4 of the peak field when it reaches the anode plate. The solenoid used was the TTF2/VUV-FEL model[22], since it has well characterized field maps available. The technique described in [21] comes close to finding the field needed in the solenoid to compensate the bunch however modeling is necessary to set the field exactly, since the analytic model does not take into account differences in focusing along the length of the bunch due to chromatic or transverse size differences. Using the distribution from the gun simulation as an input, ASTRA runs varying the solenoidal magnetic field around the analytic value are performed looking for the optimal working point. The correct solenoid setting should give a minima in $\sigma_r$ and a local maxima in $\varepsilon_r$ at the entrance to the cryomodule, with $\sigma_r$ at the entrance of the linac section about 0.43 times that of the maximum in the solenoid. As mentioned before, the solenoid setting must also preserve the peak bunch current at the entrance to the first cryomodule. This tends to be the problem, since the bunch has a 100 keV chirp on 4 MeV average kinetic energy due to the space charge by the time it leaves the gun and that translates to a velocity difference of about 1E5 m/s between the front and back of the 0.19 mm RMS long bunch. So for each meter the bunch travels between the anode of the gun and the first cryomodule, it lengthens by about 0.14 mm with a proportionate drop in peak current. A three meter drift prior to the first cryomodule reduces the peak current by $(0.19\text{mm}+3 \times 0.14\text{mm}) / 0.19\text{mm}$ or just over a factor of three. To maintain the peak current the cryomodule entrance is moved closer to the cathode from the nominal working point. Since the beam is space charge dominated up to ~60 MeV [23], by choosing low gradients in the first few cells the emittance oscillation can be allowed to reach a minimum prior ‘freezing’ the beam. The change in peak bunch current in the first few cells is abated by phasing the first cavity in the cryomodule to control the $dp/z$; reversing the sign of the energy spread across the bunch and preventing it from continuing to spread out.
So the approach I’m using is to set the solenoid at the nominal value specified by the transverse emittance and beam sigma envelopes. Then moving the cryomodule closer to the gun until the entrance is at the point at which the peak current is at fifty amps as determined by the solenoid simulations and then calculating the amplitude of the field in the first cavity based on the beam gamma and sigma according to the invariant envelope equations. Adjusting the slope of the rf field in the first cavity to reverse the sign of the dp/z by setting the cavity amplitude and phase such that the resulting average gradient is the analytic value and the imposed dp/z across the bunch, assuming a 2 psec long bunch, is +/-100 keV to remove the space charge chirp. Then adjusting the gradients in the other cavities of the module to set the final energy spread and allow the emittance envelope to reach a minimum before the beam becomes emittance dominated. Once the gradients and phases in the linac are set, a simulation is run to look at the emittance envelope, peak current and beam sigma in the linac and verify that everything worked. Usually this requires two or three (or more) iterations even starting with the analytical values for each cavity, but it gives a solution close to an optimal value.

The normal process for a set of simulations then is:

- Generate a field map for the gun cavity using Superfish;
- Use ASTRA to simulate a particle to just beyond the gun cavity with the “PHASE_SCAN” option turned on to determine the cavity phase for minimum dp/p (ignores space charge) and maximum p.
- Select a gun cavity phase which compromises energy gain, energy spread and peak bunch current.
- Take the output from the gun simulation and use the sigma x and beam gamma at the centerline of the solenoid position to calculate the analytic solenoid strength; run ASTRA simulations for solenoid values of +/- 30 G in 4 G steps.
- Select a solenoid setting which has the correct ratio of sigma x between the centerline of the solenoid and the waist of the beam (~0.43) for the optimal envelope.
- Take the output from that simulation, look where the peak bunch current drops to 50 amps and move the entrance of the first cavity of the cryomodule to that point;
- Use the calculated sigma x and beam gamma to calculate the gradient needed in the first cavity of the cryomodule to match the focusing needed by the beam.
- Assuming a 2 psec long bunch, adjust the amplitude and phase in the first cavity in the cryomodule to have the calculated average gradient and a 200 keV delta p.
- Set the second through fourth cavities to the amplitude and phase needed to have 1% dp/p and the calculated gradient.
- Set the fourth through eighth cavities to the maximum amplitude and phase them to give 1% dp/p.
- Simulate the linac using the output from the solenoid simulation as input. Look at the transverse emittance vs z and adjust the cavity gradients to allow the emittance oscillation to reach a minimum before the beam freezes. Similarly, look at the beam sigma envelope and adjust the gradients to balance adiabatic damping, space charge and rf focusing effects.

V. Results
The results of this process are shown in the following figures. Figure 4 shows the evolution of the transverse emittance and sigma from the cathode to the end of the first cryomodule. Note the full oscillation in the linac section of the emittance envelope even though the bunch is being accelerated. This is a demonstration that because the space
charge is so dominant at these high charge densities, the linac can be moved closer to the gun without overly compromising the emittance downstream so long as the gradients in the first few cavities are kept small. The normalized projected transverse emittance at the end of the linac is 0.8 mm-mrad and the initial thermal emittance at the cathode is 0.74 mm-mrad. So there is only ~10% increase in the emittance of the beam from the cathode to 100 MeV, at least in the simulation. The transverse sigma envelope also follows a smooth, asymptotic curve from the solenoid to the end of the linac. Another graphical test for a well compensated beam is the bunch profile. For a well compensated beam, the bunch will maintain an ellipsoidal distribution from the solenoid until it becomes fully relativistic. Figures 6 and 7 show the bunch profiles at the center of the solenoid, the entrance to the linac, after four cavities and at the end of the first cryomodule. This solution is slightly under focused going into the module and slightly overfocused as it exits, but is still similar to the profile in [24]. Finally there is the slice emittance and E vs z profile at the end of the linac shown below. Although there is still some numerical noise in the energy distribution, both parameter sets will work for the WiFEL accelerator.
Footnotes

4. Bas van der Geer, Production of ultra-short, high-brightness waterbag bunches, Future Light Sources 2006, DESY, Hamburg, Germany
5. V. Miltchev, Investigations on the transverse phase space at a photo injector for minimized emittance, Dissertation, University of Berlin, Feb 3, 2006
6. P. Emma, Bunch Compression, 17th Advanced Beam Dynamics Workshop on Future Light Sources, Argonne, Ill 1999
8. A. Facco, et al., “Construction of a 161 MHz, beta=0.16 Superconducting Quarter Wave Resonator with Steering Correction for RIA”, LINAC 2004, KEK, 2004
9. C. Beard, J. Teichert, EUROFEL-Report-2006-DS5-023
13. Holsinger and Halbach, SUPERFISH, LAACG, LANL 2003
15. J. Rozensweig and G. Travish, Design Considerations for the UCLA PBPL Slit-Based Phase Space Measurement Systems, UCLA, 1994
20. R. Legg, SRC Technote 220, 28 July 2007

APPENDIX 1.
All ASTRA field maps are from the XFEL website or from Superfish models provided there except for the half wave cavity map which is from the Superfish model below..

halfwave200.af
filename: qw200MHz Rev_H.am
Quarter-wave SRF photoinjector @ 200 MHz

&REG KPROB=1                     ; Superfish problem
MAT=1                            ; Material air or empty space
FREQ=190.0                        ; Mode frequency
FREQD=200                       ; Design frequency, for transit-time factors
BETAD=1.0                        ; Design beta
NBSUP=1,NBSLO=0,NBSRT=1,NBSLF=1  ; Boundary conditions
LINES=1                           ; Fix internal points on line regions
ICYLIN=1                         ; X=>Z,Y=>R, cylindrical coordinates
NORM=0                           ; Normalize to EZERO
EZERO=1000000.                ; Accelerating field
;SCCAV=1,                     ; Superconducting elliptical cavity
DTL=1,                           ; Drift tube linac
RMASS=-1                         ; Rest mass value or indicator
EPSO=1.0E-6                      ; Mesh optimization convergence parameter
IRTYPE=1                         ; Rs method: Superconductor formula
TEMPK=4                          ; Superconductor temperature, degreesK
TC=9.2                           ; Critical temperature, degrees K
RESIDR=10.D-9                  ; Residual resistance
XDRI=10.0                         ; Drive point X coordinate
YDRI=12.0                         ; Drive point Y coordinate
DSLOPE=-1                        ; Allow convergence in 1 iteration
DX=0.1                           ; Mesh spacing in X direction
CONV=1.0
&

;half wave structure
&PO X=12.65,Y=10.0 &
&po nt=5, radius=7.0, x=5.65, y=17.0 &
&po nt=5, radius=7.0, x=12.65, y=24.0 &
&PO X=68.25, Y=24.0 &
&po nt=5, radius=7.0, x=75.25, y=17.0 &
&po nt=5, radius=7.0, x=68.25, y=10.0 &
&PO X=48.5, Y=8.0 &
&PO NT=2,XO=48.5,YO=6.0, X=-2.0,Y=0.0 &
&PO X=46.5, Y=5.5 &
&PO X=46.5, Y=1.0 &
&PO X=72, Y=1.0 &
&PO X=72.0, Y=0.0 &
&PO X=34.4, Y=0.0 &
&PO X=34.4, Y=0.45 &
&PO X=32.4, Y=0.45 &
&PO X=32.4, Y=0.5 &
&PO X=34.4, Y=0.5 &
&PO NT=2, X0=34.5071068, Y0=0.5, X=-0.120710678, Y=0.120710678 &
&PO X=34.5, Y=5.74142136 &
&PO NT=2, X0=32.2, Y0=5.74142136, X=0.0, Y=2.3 &
&PO X=12.65, Y=10.0 &

ASTRA INPUT FOR WiFEL INJECTOR

&NEWRUN
Head='Charge extraction vs. phase; 40MV/m 0.20nC 30fsec long initial pulse'
RUN=1,
Loop=F, NLoop=1,
Distribution = 'ellipsegun50k.ini' ! Distribution = 'dcgun2.ini'
Imagnetized=.F
EmitS=.T
PhaseS=.T
T_PhaseS=.F
TrackS=.T
RefS=.T
TcheckS=.T
CathodeS=.T
High_res=.T
TRACK_ALL=.T, PHASE_SCAN=F, AUTO_PHASE=T
check_ref_part=.F,
ZSTART= 0.0, ZSTOP=22
Zemit=200
Zphase=200
H_max=0.001
H_min=0.000001
/

&SCAN
Loop=F
LScan=F
Scan_para='Phi(1)'
S_min=72, S_max=92, S_numb=11
FOM(1)='rms.energy'
FOM(2)='cor.energy'
FOM(3)='hor.emit'
FOM(4)='hor.spot'
/

&CHARGE
Loop=F
LSPCH = T
Lmirror=T
Nrad=50, Nlong_in=100
Cell_var=3.0
min_grid=0.1D-6
Max_scale=0.01
Max_count=100
/

&Aperture
/

&FEM
/

&CAVITY
Loop=.F,
LEFieLD=.T,
FILE_EFieLD(1) = 'fields/hwave2.dat',
Nue(1)=0.2, MaxE(1)=40.0, Phi(1)=+8, C_smooth(1)=10, C_pos(1)=0
FILE_EFieLD(2) = 'fields/teslacav13.dat',
Nue(2)=1.3, MaxE(2)=16, Phi(2)=-49.5, C_smooth(2)=10, C_pos(2)=2.6,
FILE_EFieLD(3) = 'fields/teslacav13.dat',
Nue(3)=1.3, MaxE(3)=10, Phi(3)=-21.5, C_smooth(3)=10, C_pos(3)=3.985,
FILE_EFieLD(4) = 'fields/teslacav13.dat',
Nue(4)=1.3, MaxE(4)=12, Phi(4)=-21.5, C_smooth(4)=10, C_pos(4)=5.37,
FILE_EFieLD(5) = 'fields/teslacav13.dat',
Nue(5)=1.3, MaxE(5)=18, Phi(5)=-21.5, C_smooth(5)=10, C_pos(5)=6.755,
FILE_EFieLD(6) = 'fields/teslacav13.dat',
Nue(6)=1.3, MaxE(6)=28, Phi(6)=-21.5, C_smooth(6)=10, C_pos(6)=8.14,
FILE_EFieLD(7) = 'fields/teslacav13.dat',
Nue(7)=1.3, MaxE(7)=28, Phi(7)=-21.5, C_smooth(7)=10, C_pos(7)=9.525,
FILE_EFieLD(8) = 'fields/teslacav13.dat',
Nue(8)=1.3, MaxE(8)=28, Phi(8)=-21.5, C_smooth(8)=10, C_pos(8)=10.91,
FILE_EFieLD(9) = 'fields/teslacav13.dat',
Nue(9)=1.3, MaxE(9)=28, Phi(9)=-21.5, C_smooth(9)=10, C_pos(9)=12.295,
FILE_EFieLD(10) = 'fields/teslacav13.dat',
Nue(10)=1.3, MaxE(10)=28, Phi(10)=-21.5, C_smooth(10)=10, C_pos(10)=14.795,
FILE_EFieLD(11) = 'fields/teslacav13.dat',
Nue(11)=1.3, MaxE(11)=28, Phi(11)=-21.5, C_smooth(11)=10, C_pos(11)=16.18,
FILE_EFieLD(12) = 'fields/teslacav13.dat',
Nue(12)=1.3, MaxE(12)=28, Phi(12)=-21.5, C_smooth(12)=10, C_pos(12)=17.565,
FILE_EFieLD(13) = 'fields/teslacav13.dat',
Nue(13)=1.3, MaxE(13)=28, Phi(13)=-21.5, C_smooth(13)=10, C_pos(13)=18.95,
FILE_EFieLD(14) = 'fields/39ghzcavity.dat',
Nue(14)=3.9, MaxE(14)=17, Phi(14)=180, C_smooth(14)=10, C_pos(14)=19.85,
/

&SOLENOID
Loop=F,
LBFieLD=.T,
FILE_BFieLD(1)='fields/solenoid.dat', MaxB(1)=0.276,
S_pos(1)=0.352, S_smooth(1)=10, S_xoff(1)=0.0, S_yoff(1)=0.0
/

&QUADRUPOLE
/

ASTRA INPUT FOR INITIAL DISTRIBUTION

&INPUT
FNAME = 'ellipsegun50k.ini'
Add=.F.
N_add=1
IPart=50000
Species='electrons'
Probe=.True.
Noise_reduc=.T.
Cathode=.T.
Q_total=0.20E0
Ref_zpos=0.0E0
Ref_clock=0.0E-5
Ref_Ekin=0.0
Dist_z='uniform ellipsoid',
sig_clock=1.5E-5, sig_x=0.8E0, sig_y=0.8E0
Nemit_x=0.74E0, Nemit_y=0.74E0
/