HALF WAVE INJECTOR DESIGN FOR WiFEL*

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Abstract

Seeded FELs will require exceptional beam quality. The Wisconsin FEL (WiFEL) requires average current of 1 mA, peak currents of greater than 1 kA with less than 1 mm-mrad transverse slice emittance and 10^{-4} $\delta p/p$ at the undulator. To perform bunch compression after the injector without allowing micro-bunching requires very smooth bunch energy and density profiles with relatively low compression ratios. An injector which uses a low frequency, superconducting half wave resonator gun combined with self-inflating ellipsoidal bunches[1] to meet those requirements is described. The superconducting radio frequency TEM-class cavities have been in use for more than 25 years and because of their potential for flat field profiles, are desirable as electron gun structures. A Superfish[2] model and field map of the specific gun cavity is presented. ASTRA[3] simulations from the cathode to 120 MeV are provided, along with a description of the technique used to emittance compensate the space charge induced energy chirp while maintaining the peak bunch current.

WiFEL REQUIREMENTS

The design of the Wisconsin FEL incorporates a 2.2 GeV superconducting linac supplying electrons to six FELs. The electron beam requirements for each FEL are very stringent requiring 1 kA, 30 fsec flat top bunches with less than 1 mm-mrad normalized transverse slice emittance and less than 10^{-4} slice energy spread. The accelerator is required to supply each of the six FEL end stations simultaneously at up to a 1 MHz repetition rate for user operations, requiring 1 mA average current. The CW bunch train mandates the use of a CW electron source.

The 1 kA flat top current profile necessitates bunch compression of some form in the linac. The two options are velocity bunching or magnetic bunching, but given the CW/SRF nature of the linac, and the difficulty of velocity bunching without an external magnetic field, magnetic bunch compression was chosen for the WiFEL. Magnetic compression depends on the $R_{56} \times \delta p/p$ to induce a change in the bunch length. The amount of compression is limited by three things: the allowed residual δp at the FEL, the minimum momentum at which the bunch becomes emittance, rather than space charge, dominated, and the CSR induced microbunching and emittance dilution produced by the R_{56} used for the compressor[4]. Linearity of time/energy distribution limits max compression. In the case of the WiFEL, maximum compression is about 20, which means the injector must provide a ~50 A peak current upstream of the first bunch compressor.

The magnetic bunch compressors are also very sensitive to longitudinal energy modulations across the bunch. Gain factors (conversion of energy modulation to current modulation) of 10^5 or more for certain parameter sets have been calculated[5]. Figure 1 shows a 10^{-4} $\delta E/E$ doubling the density modulation after the compressors. The injector must provide a bunch distribution which suppresses this growth of density modulations. This condition is satisfied by a three-dimensional, ellipsoidal distribution with constant charge density. To generate an ellipsoidal bunch several options are possible[6], but the most promising is the "blow-out" mode[1].

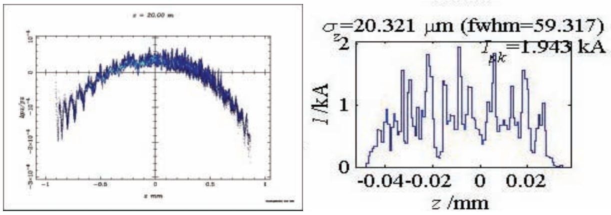

Figure 1: Non-linear energy modulation calculated by ASTRA (left) converted to density modulation in a LiTRACK simulation of magnetic compressors (right).

The charge density of the bunch in "blow-out" mode is limited by 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 thermal emittance; at 1mm rms radius the thermal emittance for Cs_2Te reaches about 1 mm-mrad[7]; 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 σ on the cathode spot is observed, then the electric field on the cathode necessary to achieve 50 A peak is about 37 MV/m[8]. 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.

The 200 pC bunch charge from the injector was selected as the minimum which can provide the FEL bunch current/time profile after compression allowing for the jitter between the electron bunch and seed laser pulse arrival times.

SRF STRUCTURE SELECTION

An SRF electron gun is necessary to provide the high quality, high peak current beam for a seeded FEL. The

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SRF gun designs presently available use L-band elliptical cavities, with an initial half cell that is run significantly off crest to compensate for energy spread caused by longitudinal space charge (LSC). For this application, however, a 200 MHz half wave resonator structure has been selected to provide better beam properties than the higher frequency elliptical cavity designs. Since the charge density in the required blow-out mode bunches goes as the electric field, E_0, squared, when higher frequency cavities are run at an angle, ϕ radians, off-crest, the charge density will have a profile which goes like $[E_0\cos(\phi \pm \pi z_{bunch}/\lambda_{rf})]^2$ along the bunch, ignoring the bunch's phase slip. As noted above, the variation in charge density produced may be enhanced by the bunch compressors. The field profile in the half wave cavity is also relatively insensitive to errors between the drive laser timing and the cavity rf because the gap is much shorter than the rf wavelength, providing a pseudo-DC acceleration. Finally the RF magnetic field per MV/m is about half the value of an L-band elliptical cavity, meaning that twice the gradient is possible for a given quench field value. Of course field emission may also limit the max gradient.

Operationally, BCS losses are proportional to the frequency squared, making 4K operation possible at lower frequencies. The cavity also has lower circulating rf currents in the cathode region making a load lock and rf choke much simpler. Solenoids, as used in emittance compensation, have already been integrated into close proximity to this style cavity[9], potentially improving the emittance compensation of the gun.

The difficulties for the half-wave cavity are the same as with all photocathode SRF guns. Few examples and even fewer tests leave the questions about cavity Q degradation due to cathode material migration and maximum E field limitations open. A problem unique to a gun designed around a blow-out mode bunch is the need to mitigate the LSC induced energy spread on the bunch. If the bunch's energy distribution is not corrected, the space charge forces lengthen the bunch in the solenoid/drift region prior to the first cryomodule. This lowers the peak bunch current in a linear fashion potentially causing the bunch to no longer meet the FEL requirement.

CAVITY DESIGN

The exit energy from the gun was increased to ~5 MeV, significantly slowing the lengthening of the bunch after the gun. This was done by lengthening the gap between the cathode and anode to 15 cm, and converting the cavity shape from a quarter cavity to a half cavity to flatten the field profile in the anode to cathode gap. The Superfish model for the gun is shown in Figure 2. The folded structure to the left of the cathode is a quarter wave choke joint based on the Tunnel Dust and BNL [10] work.It allows the cathode to be a warm ,Cs_2Te film which is fabricated in an external preparation chamber. A Pierce like geometry was added to the cathode electrode in order to enhance the transverse focusing. The inset shows the E field profile along the *z* axis in the gap. The cavity has a B_{pk}/E_{pk} ratio of about 1 mT / MV/m and E_{peak} is about 1.3 times the peak value along the *z* axis.

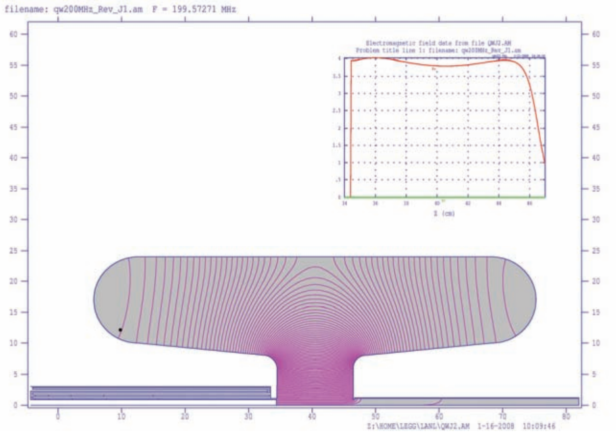

Figure 2: Superfish field map and profile between cathode and anode

ASTRA MODEL

The generation of the initial charge pancake distribution is described in [11]. 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 (see figure 3). In this case, -8° from crest (262° cavity phase in figure 3) was selected, since this gave the maximum peak current from the gun and close to the maximum kinetic energy. The particle distribution produced by the simulation at the end of the cavity is then taken and set as the input for the emittance solenoid compensation scans. Longitudinal space charge produces a ±50 keV chirp along the bunch as it leaves the gun. In an L or S band gun this is compensated for by phasing the gun cavity so the rf induced energy spread bucks the space charge induced energy spread, but in a DC or low frequency gun the bunch subtends too little of the rf waveform to be easily affected. The standard emittance compensation solution used [12] however, assumes that the beam has a narrow energy spread and its σ' is much less than 1. Neither of these assumptions is valid in this case. Therefore, the emittance compensation scheme must change, adjusting the solenoid strength and position of the first cryomodule to accelerate the bunch before the

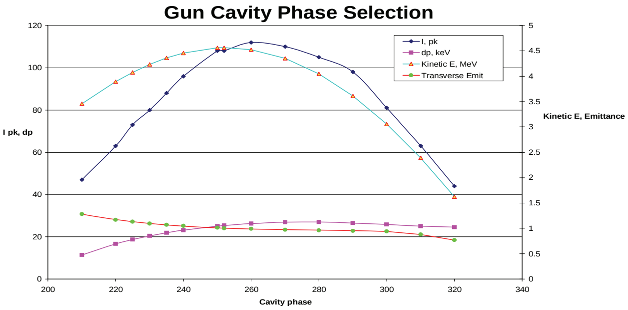

Figure 3: Beam properties vs cavity phase

peak current drops while maintaining a reasonable emittance envelope.

Emittance compensation is done using a solenoid downstream of the anode which focuses 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 strength along the *z* axis at the anode plate is less than 10^{-4} of the peak field. The technique described in [13] analytically approximates the field needed in the solenoid to compensate the bunch, however modeling is necessary to determine the precise field, since the analytic model does not take into account differences in focusing along the length of the bunch due to chromatic and transverse distribution differences. The correct solenoid setting in the classic emittance compensation scheme should give a local minima in σ_r and a local maxima in ε_r at the entrance to the cryomodule. The σ_r in the solenoid should be ~2.3 times the local minima, setting the solenoid strength and cryomodule position. Unfortunately, the LSC induced energy spread causes the bunch to lengthen by about 0.14 mm for every meter traveled by the 0.34mm long bunch. A three meter drift prior to the first cryomodule reduces the peak current by just over a factor of two. To maintain the required peak current the cryomodule entrance is moved closer to the solenoid from the nominal working point and the first cavity in the cryomodule is phased to reverse the sign of the energy spread across the bunch preventing it from continuing to spread. Since the beam is space charge dominated up to ~60 MeV, by choosing low gradients in the next few cells of the module, the emittance oscillation can be allowed to reach a minimum prior to ‘freezing’ the beam.

RESULTS

The results of this process are shown in the following figures. Figure 4 shows the evolution of the transverse emittance and size from the cathode to the end of the first cryomodule (composed of eight TESLA-type cavities). 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. 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. Figure 5 shows *x* vs *z* in the bunch reference frame from the cathode to the end of the first module. The bunch is slightly over focused at the end but the solution meets the WiFEL requirements.

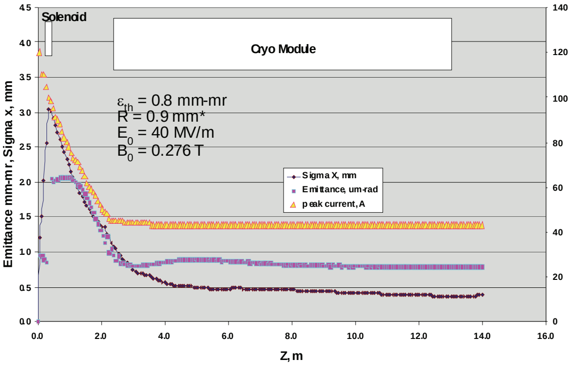

Figure 4: Bunch properties vs *Z* position

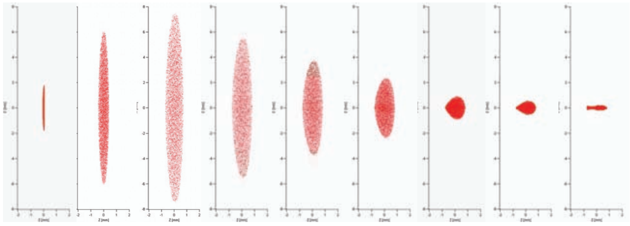

Figure 5: Bunch development from cathode to end of first cryomodule

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