SRF PHOTOINJECTOR R&D AT UNIVERSITY OF WISCONSIN*

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Abstract

Next generation light sources will enable significant new science in the many disciplines including atomic and fundamental physics, condensed matter physics and materials sciences, femtochemistry, biology, and various fields of engineering. The source we propose, and the experimental methods it will spawn, will generally be qualitatively new and have high impact through ultrahigh resolution in the time and frequency domains combined with full transverse coherence for imaging and nanofabrication. Continuous wave FEL's provide the highest beam brightness[1], full temporal and transverse coherence and the potential for ultra short photon pulses at high repetition rates that the science requires. But the hardware, in particular the injector, to build such a light source has not been demonstrated yet. University of Wisconsin, in collaboration with the Naval Postgraduate School, has been engaged in a design contract with Niowave Inc to design a superconducting rf electron gun to be used for such a source. This design work and our collaboration with the Naval Postgraduate School in the construction and test of their SRF gun will allow us to produce a prototype device in a timely and cost effective manner. The design for such a development enables a User facility with the capability to explore the science in the grand challenges laid out by DOE BESAC[2] and the Science and Technology of Future Light Sources white paper[1].

BACKGROUND AND OVERVIEW

The challenges laid out in the DOE BESAC grand challenges in science and energy require new photon sources. Current accelerator technology cannot support the required goals for those sources technically. Additional accelerator research and development is required in order to enable the science in the grand challenges. The University of Wisconsin has proposed a seeded FEL, the Wisconsin Free Electron Laser (WiFEL), which is differentiated from today's synchrotron facilities or laser sources because it combines high power and coherence for the first time in the 1 to 100 nm range. The source we propose, and the experimental methods it will spawn, will generally be qualitatively new and have high impact through ultrahigh resolution in the time and frequency domains combined with full transverse coherence for imaging and nanofabrication.

The key features of the facility we envision are demanded by the scientific mission. A seeded FEL would take advantage of the flexibility, stability, and high average pulse rates available from a continuous-wave (CW) superconducting linac fed by a superconducting photoinjector. For example, a second generation seeded FEL[1] is capable of producing the very bright and short pulses required to produce the science. In order to produce beams of the highest quality, the electron beam will be seeded with high harmonics of laboratory lasers. The required electron beam requirements at the insertion devices for such a device are shown in Table 1.

Table 1: FEL Requirements

I ave, Rf power coupler limited	~ 1 mA
I peak at Undulator	1000 Amps
DI / I at Undulator	10% Max
Normalized ε Transverse	<1 mm-mrad
Bunch length, rms	70 fsec
Charge/bunch (derived)	200 pC
Gun Repetition frequency	Up to 5 MHz

The one milliamp limit for a linac based light source in the table is a function of the coupler limitations of the present generation of high gradient L-band superconducting modules. Both Tesla and Jefferson Lab 100 MeV cryomodules have couplers which can handle about 10 kW of rf power per cavity with about 10 MeV of acceleration per cavity, limiting their current handling to about 1 milliamp without energy recovery. Certain cavities such as the JLAB FEL injector quarter cryomodule and the Cornell eight cell modules can surpass this limitation, but these modules are much larger and more expensive per MeV of acceleration in both procurement and in tunnel footprint required.

The peak current required by the insertion device is about 10^3 amps with the FEL-gain proportional to the electron density in the bunch[3]. Only 10% ΔI/I modulation on the current waveform is allowed during the interaction between the seed laser and the electron bunch. These modulations produce enhanced spontaneous radiation which competes with the seed laser to modulate the rest of the electron bunch; in the worst case, the spontaneous radiation produced by the charge density fluctuations may destructively interfere with or produce sidebands around the seed laser wavelength. The User community the WiFEL is designed to serve also expect very little variation in optical power just as they would receive from a synchrotron light source. This 10% ΔI/I limitation is exacerbated by the magnetic bunching chicanes which squeeze the bunches longitudinally after the injector to reach the necessary kiloampere levels in the undulators but can also cause sharp density spikes in the compressed bunch by amplifying existing longitudinal modulations. Gain factors can reach 10^6 for a two chicane system [4], Fig 1. To mitigate this effect, weak compressors are used, increasing the peak current required from the gun.

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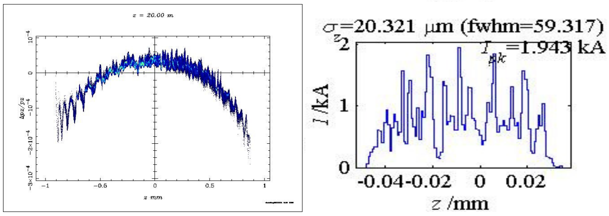

Figure 1. Non-linear energy modulation from ASTRA being converted to density distribution in LiTRACK simulation of magnetic compressors.

For a given photon energy produced by the FEL, the required electron beam emittance is inversely proportional to the beam energy, at least down to a beam energy of 50 MeV.[5] Since the beam energy is derived from the accelerator which is the largest cost in the project, the transverse emittance must be minimized to reduce the number of accelerator modules and the cost of the facility. Recent results at LCLS [6] suggest <1 mm-mrad is possible, but an emittance compensation scheme to correct all but the initial thermal emittance is mandatory and all elements in the injector need to be thoroughly tested for coupling and chromaticity.

These three requirements for a seeded FEL put tremendous demands on the accelerator's injector. They simultaneously require electron bunches with high peak current, low transverse emittance and specifically tailored longitudinal distributions. To meet those demands, we are proposing an SRF electron gun for application to a seeded FEL system. The superconducting rf gun is the newest technology with first operation of a gun at FZD in 2002[7]. It promises gradients of 40 MV/m and exit energies >4 MeV.

The superconducting rf gun we are proposing is a 200 MHz quarter wave resonator design. The University of Wisconsin has been doing extensive modeling of the electrical, rf and beam dynamics properties of the cavity for the last year and a half. The low frequency has several advantages. The device can operate at 4.2 K since the BCS losses go as the frequency squared. The accelerating gap is small compared to the rf wavelength making the device pseudo DC in performance. This minimizes the effect of phase slip as the bunch traverses the gap and produces a bunch with a flat momentum vs position profile.

DESCRIPTION OF ELECTRON GUN

The SRF electron gun design which has been developed by University of Wisconsin and Niowave is shown in Fig 2. The cavity has a number of unique design features. The cathode is warm with respect to the cavity allowing the use of an alkali stoichiometric cathode with a quantum efficiency orders of magnitude higher than a metal one. This greatly reduces the power and photon energy of the drive laser. This in turn reduces its cost and complexity, with the added advantage that the specular reflections of the drive laser from the cathode do not have enough energy to produce stray electrons from the metal surfaces in the cavity, reducing downstream halo. Critical gun parameters are shown in Table 2.

Table 2. Gun Parameters

Momentum at exit of gun	4.5 MeV/c
Peak surface magnetic field	93 mT
Peak electric field on cathode	45 MV/m
Bunch length at exit of gun	0.18 mm
Rf Power loss into Helium bath	39 Watts at 4.2 K

The design utilizes a coaxial cavity filter one half wavelength long behind the cathode with an impedance of ~22 ohms to provide an rf short circuit between the cathode and the cavity while still providing a thermal gap. The outer conductor of the coaxial cavity is niobium up to

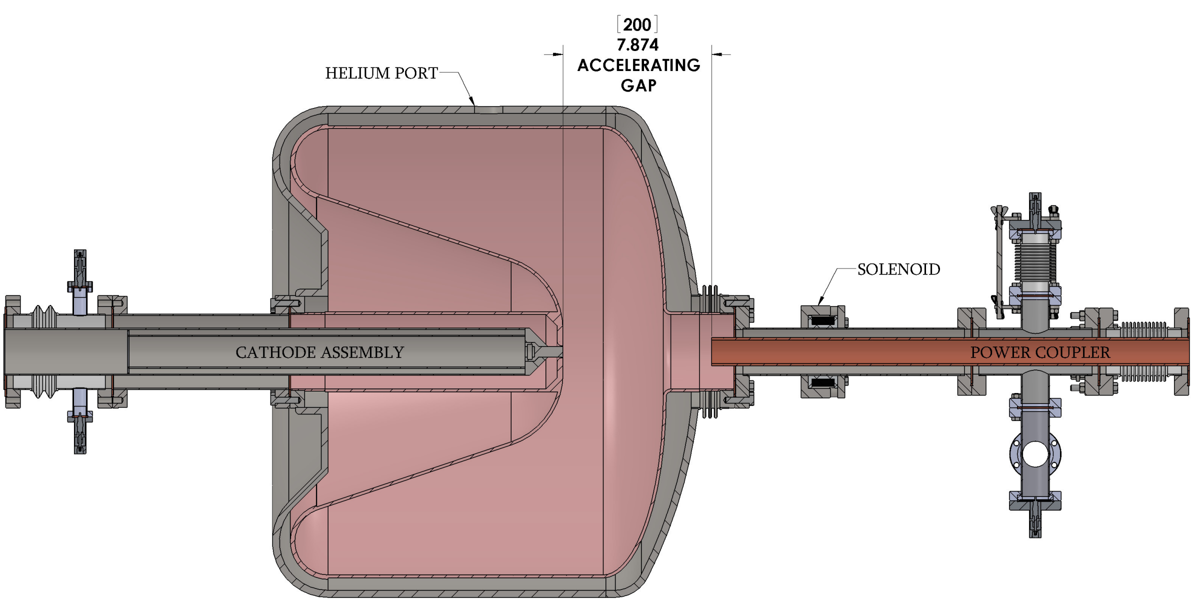

Figure 2: Quarter wave cavity design showing coaxial filter, warm cathode holder and rf power coupler.

where it mates with the stainless steel He dewar. Beyond the dewar the outer conductor becomes copper plated thin wall stainless steel which acts as the thermal break between the cold portion of the cavity filter and the room temperature portion where the rf probes, bias feed through, and alignment mount are placed. The inner conductor of the structure is made of copper plated stainless steel. It is cooled with liquid nitrogen flowing between the stainless tube and an inner liner. The LN2 reduces the radiation losses from the inner conductor of the cavity filter to the 4.2 K niobium outer conductor to less than 0.2 W; at 300 K the losses are ~30 W. The LN2 also cools the cathode holder to reduce the rf and laser heating and re-radiation into the main cavity from the cathode. The filter cavity is penetrated with rf probes to measure and provide a feedback signal for the cavity field. The fields in it are small, ranging from 60 kV/m at the shorted end to 350 kV/m at the transition into the cavity. Consequently, the rf heating in the walls in the normal conducting portions of the cavity filter calculated from Superfish are quite small, ~13.5 W, of which 10 W goes into the LN2 cooled portion of the inner conductor of the filter. The rf and laser heating in the cathode holder itself accounts for another 4 watts. This requires about 5 milliliters per second of LN2 flow to cool.

Superfish modelling indicates that in addition to the half wave coaxial cavity, a small capacitive gap is needed between the cathode holder and the cavity to minimize the radial variation of the z component of the electric field across the cathode face. This radial variation defocuses the electron beam as it leaves the cathode and degrades the downstream beam envelopes and emittance compensation. By placing a short 1 mm gap between the cathode holder and the cavity, the field is almost uniform across the face of the cathode. This desensitizes the solenoid tuning for emittance compensation.

The field map for the entire cavity is shown in Figure 3. An additional consideration was the mechanical deformation of the cavity due to vacuum loading. Finite element techniques were used to guide this process and resulted in the elliptically shaped wall on the anode end of the cavity and the thicker walled area on the cathode end of the cavity. In laying out the cavity, particular attention was paid to keeping the ratio of E peak to E cathode as low as possible and to minimizing sharp corners in the cavity which might enhance multipactoring.

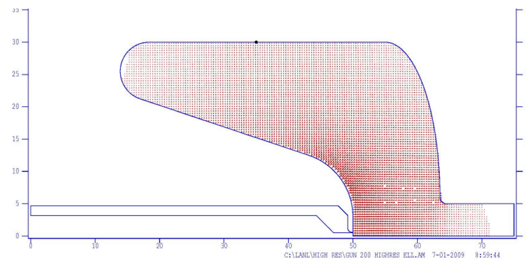

Figure 3 Electric field map from SUPERFISH for the cavity and cavity filter.

The issue of multipactor was considered for the coaxial cavity filter in a two prong manner. First simulations of the coaxial cavity were performed using FISHPACT to assess the susceptibility of the structure to multipactor. These show the cavity has no inherent problems with multipactor which might limit the field in the main cavity. We also decided to use the FZD design[8] for a cathode holder assembly which isolates the cathode electrically and allows an electrical bias to be put on it to suppress multipactor, Fig 4. This has also been suggested by BNL from their experience with SRF gun multipactor problems[9]. We also plan to use a dipole magnet on a

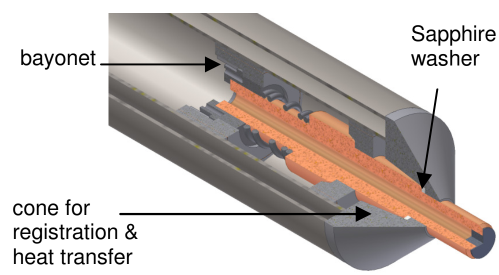

Figure 4. Cathode holder assembly

manipulator during rf conditioning, if necessary, which can be inserted into the cathode support tube behind the cathode to produce a magnetic field between the inner and outer conductor of the coaxial cavity to disrupt the orbits of potential multipactor electrons.

The gun design uses a superconducting solenoid for emittance compensation. The design has a ferrous yoke to shape the field from the superconducting coil pack. Additional mu metal shielding is also installed between the solenoid and the cavity. The solenoid has already been prototyped and tested, Fig 5.

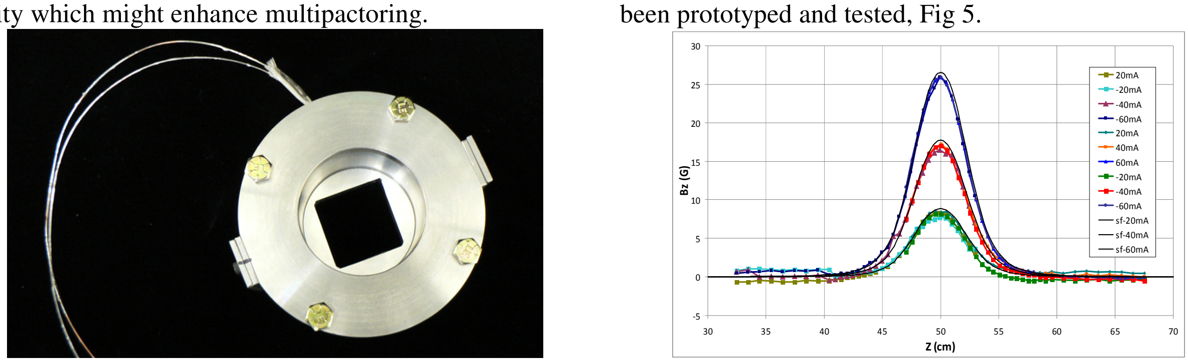

Figure 5. Photograph of SC solenoid assembly and field map

The gun uses a coaxial rf coupler as a power feed. The design can provide up to 10 kW of power to the gun based on Microwave Studio simulations, Fig 6. This is enough power for rf control with a 107 loaded Q and more than a milliamp of beam. The outer conductor of the coupler is copper plated thin wall stainless steel to supply the thermal break from the cavity to the warm rf cross. The inner conductor from the ceramic feedthrough is connected through a pressure contact to the inner conductor of the rf coupler in order to supply sufficient

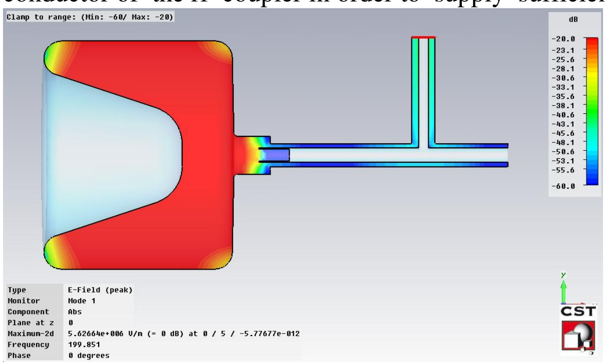

Figure 6. Microwave Studio E field map.

power to control the cavity with the desired loaded Q of 10^7. The pressure contact though allows the coupling point to be moved to vary the loaded Q of the cavity. This will allow the coupling to be varied to select the cheapest amount of rf power which can sufficiently control the cavity. The flange which mates the inner conductor of the rf coupler to the external beam pipe is actively cooled to sink the heat produced by the rf currents on the surface of the inner conductor and limit radiation losses from the coupler into the cavity to less than 1 watt. This design also exploits the inner conductor of the coupler as a beam scraper to prevent halo which originates in the high field region at the edge of the cathode holder +/-30 degrees from rf crest from propagating beyond the injector, Fig 7.

Self Inflating Bunch Formation

To meet the stringent requirements on the longitudinal distribution of the bunch produced by the gun, we propose to use self inflating (blow out mode) bunches for the FEL. Blow-out mode is a scheme in which a laser pulse much, much shorter than the final bunch length is used to create a charge pancake on the surface of the cathode which then expands under its own self space charge force to an ellipsoidal bunch with uniform charge density [10]. This technique has been successfully demonstrated at UCLA [11] and it avoids issues of laser/shaping performance or cathode emission uniformity in the production of an ellipsoidal bunch. In the 'blow out' process, many problems in the initial distribution are smoothed out, Fig 8. It also produces distributions which can be compressed and emittance compensated exceptionally well[12,13].

The downside to blow out mode is the charge density is dependant on the electric field as mentioned above and since the density in the charge pancake is very large, it requires a very high electric field on the cathode to produce the large peak currents after the bunch expands.

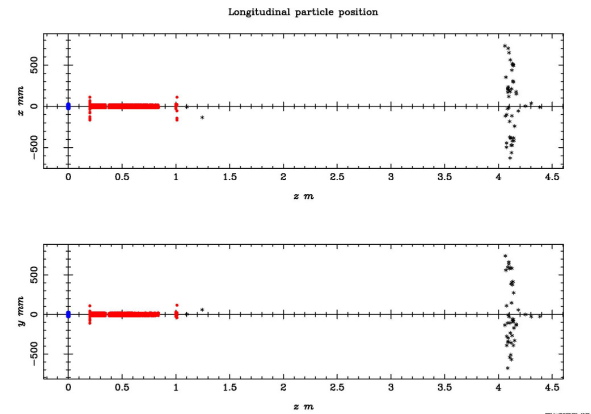

Figure 7. ASTRA[14] simulation showing lost halo particles on inner conductor of rf coupler in red. ~5 x 10^{-4} particles are transported.

The peak current can be increased by using a larger initial cathode spot, but the thermal emittance of the cathode becomes the limiting factor. The calculated limit for a peak current of 50 amps at 1 mm-mrad is 40 MV/m[15]. This is higher than can be achieved in a CW DC or NCRF electron gun and is one more reason the U of Wisconsin is proposing an SRF electron guns as a source for future FEL light sources.

The alternative to "blow out" mode is the laser shaping technique suggested by Yuelin Li[16]. This technique promises to produce ellipsoidal bunches with larger charge and lower thermal emittance than "blow out" mode can. Since the same physics is in place, charge

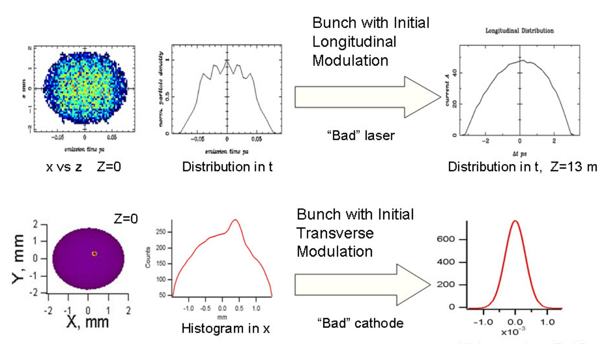

Figure 8. Blow-out mode smooths initial distribution errors

density and peak current still varies as the electric field squared using a shaped laser pulse, but the cathode spot and thermal emittance can be made smaller since the bunch charge can be produced gradually, rather than in a pancake. The SRF gun can also use this technique to produce bunches with peak currents much greater and with lower emittance than possible with either the CW DC or NCRF gun.

ASTRA and IMPACT-T simulations of the proposed gun using 'blow out' mode show the gun can produce electron bunches which meet the requirements of a seeded FEL, Fig 9. The emittance compensation scheme[17] used is the same as LCLS is using successfully. In this scheme, the gun is followed by a high quality solenoid magnet which sets the emittance envelope going into the first linac section. 'Blow-out' mode imparts a large space charge induced dp versus z along the bunch which causes the bunch to lengthen as it moves away from the cathode. As the bunch does so, the peak current gets lower. To mitigate this process, the linac section is moved closer to the gun and the first cavity is phased to reverse the dp versus z. The gradient of the rf field must also be scaled to allow the emittance oscillation to be completed prior to the emittance being 'frozen' by the increased energy of the beam[18]. If the laser shaping technique described above can be applied, significantly better beam properties will result.

CONCLUSIONS

The University of Wisconsin has been working on the design for an SRF electron gun designed specifically to address the needs of a CW, soft x-ray, seeded FEL. The design utilizes the self inflating bunch scheme in order to produce ellipsoidal bunches with sufficiently smooth longitudinal distributions that downstream magnetic compression can be performed without longitudinal density spikes, detrimental to the User, appearing. The design includes a warm stoichiometric cathode and holder which reduces the required drive laser power, a coaxial filter to isolate the cathode holder thermally from the superconducting cavity, and a coaxial rf input coupler at the anode. The cavity is a quarter wave resonater with an accelerating gap much shorter than the rf wavelength. The injector meets the specification of a 1 mA average beam, at 50 amps peak at less than 1 micrometer-rad transverse slice emittance. By working backward from the requirements of the experimental User, through the accelerator, to the injector, the vision of the gun has been guided to this specific design. We have specifically addressed the issues of the coaxial filter, mechanical loading and thermal management of the cavity.

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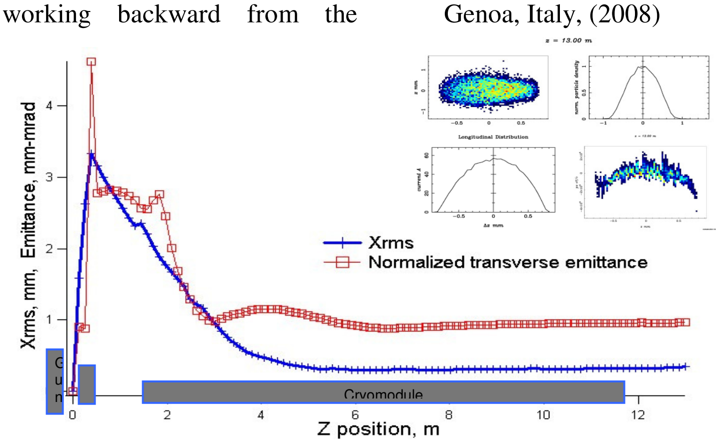

Figure 9. Beam envelopes for WiFEL injector using ASTRA