A SUPERCONDUCTING LINAC DRIVER FOR THE WISCONSIN FREE ELECTRON LASER*

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Abstract

We present an initial design of the driver for the Wisconsin VUV/Soft Xray FEL facility, which will provide high intensity coherent photons from 5 eV to 0.9 keV. It uses a 2.2 GeV, L-band CW superconducting linac with a 1.7 GeV tap-off to feed the lower energy FELs. In order to support multiple high rep-rate FELs, the average design current is 1 mA. Sub-nanocoulomb bunches with normalized transverse emittances of order 1 μm are generated in a photoinjector for beamlines operating at repetition rates from kHz to MHz. Multi-stage bunch compression provides 1 kA peak current to the FELs, with low energy spread and a suitable current profile. Compressed bunch lengths of order 100 fs will allow generation of photon pulses in the range 10 to 30 fs using seeded FELs. Consideration has been given to removing the residual energy chirp from the beam, and minimizing the effects of space charge, coherent synchrotron radiation, and microbunching instabilities. A beam switchyard using RF separators and fast kickers delivers the desired electron bunches to each of the FELs. Details of the design are presented, including those areas requiring the most development work.

ELECTRON BEAM REQUIREMENTS

The Wisconsin FEL is designed to produce fully coherent radiation over the entire range from 5 to 900 eV [1,2]. Successful operation of the FEL places several requirements on the electron beam properties. In order to reach the desired GW power levels, keep gain lengths short, and seed laser power levels reasonable, the FEL is designed with a 1 kA peak electron beam current, 200 keV energy spread, and a normalized transverse emittance of 1 μm. Lasing will occur on a 30 fs slice of each electron bunch. However, to allow for timing jitter, the charge in each bunch is ~200 pC.

PHOTOINJECTOR

The electron injector must supply the electron bunches which have the necessary transverse and longitudinal properties to allow bunch compression to the required levels while minimizing the collective effects in the accelerator. A bunch profile which meets this requirement is ellipsoidal with uniform charge density [3].

To create an ellipsoidal bunch with uniform charge density, an ultra-short laser pulse with a hemispherical transverse profile can be used to produce a dynamically formed ellipsoidal bunch [4]. The limit on the dynamically formed bunch approach is that the charge density of the bunch is only dependant on the electric field applied to the cathode. The maximum compression ratio which can be easily achieved while preserving the beam parameters necessary to lase is about 20, giving an initial peak bunch current of 50 A. At a 1 mm RMS emission radius the electric field on the cathode necessary to achieve 50 A peak is about 29 MV/m. Such a field is within the reach of an SRF electron gun.

A possible solution using 200 pC bunches and the FZR 3.6 cell SRF electron gun [5] has been modeled using ASTRA [6]. The FZR structure was chosen as the most mature SRF electron gun. In order to achieve a peak field of 29 MV/m on the cathode with the FZR structure, the cathode has been artificially allowed to move forward into the cavity by 8 mm to reach the peak field point in the first half cell. With a phase of 88°, the bunch evolves from a 30 fs RMS pulse with a 0.95 mm σ_x, with a hemispherical transverse profile according to a 50 A peak, 0.4 mm σ_z, bunch of ellipsoidal profile, shown in Fig. 1.

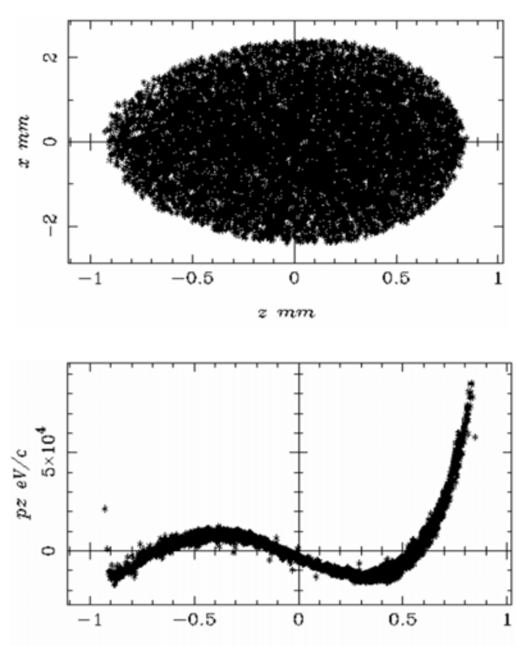

Figure 1: Bunch profile (top) and non-linear deviation from nominal energy (bottom) at 10 MeV.

*Work supported by the University of Wisconsin – Madison, MIT, ONR, AFOSR and DESY. SRC is supported by the U.S. National Science Foundation under Award No. DMR-0537588.
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Future plans are to explore the design of an SRF 1.5 cell gun [7] which optimizes the cathode field to boost the peak current which the gun can deliver while still delivering outstanding beam properties for the FEL.

SUPERCONDUCTING LINAC

The main requirements for the 2.2 GeV L-Band CW linac are well within reach of the current state of the art of superconducting RF technology. The FEL design concept, with high harmonic generation seeding and cascading scenarios that do not require fresh bunch segments, allows lasing with only 200 pC bunch charge. With only 1 mA of accelerated beam, several lasers can be simultaneously fed at 1 MHz repetition frequency each (e.g., for photoemission spectroscopy) with other lines operating at lower repetition rates (e.g., for pump-probe experiments). The 1500 MHz CEBAF upgrade cavity [8] provides a reference point, with gradient of ~20 MV/m, CW Q of ~8×10^9, RF power handling capability to accelerate >400 μA beam current, and a dynamic-static heat load of 300 W for a 100 MeV cryomodule. Amplitude control of less than 0.01% (better than required) and phase control of 0.05º (within about a factor two of what is required) have been achieved.

BUNCH COMPRESSORS

To take the 50 A bunch from the injector to the 1 kA bunch required by the FEL, we must accelerate the bunch while compressing it by a factor of 20 at sufficiently high energy that space charge effects do not degrade the bunch. We are studying a 1.3 GHz superconducting linac with 3.9 GHz harmonic cavities, utilizing two-stage compression. The effect of CSR wakes is reduced by utilizing compressors with low R_{56} and a relatively large chirp. The combination of the low wakefields of a SC linac and relatively few cavities after the final compression requires active dechirping of the beam using the linac. Acceleration ~33º off-crest after final compression reduces the residual chirp to acceptable levels for FEL operation. A preliminary design, shown in Fig. 2, compresses by a factor of 8 at energy of 215 MeV and a factor of 2.5 at 485 MeV. To model compression and determine appropriate parameters, we have performed longitudinal tracking with linac wakes [9], where a resistive wake after each chicane approximates CSR. This is a valid approximation for dipoles in which edge radiation dominates over classical CSR. Longitudinal tracking shows satisfactory performance for parabolic bunches of 50 A peak current, 200 pC, and an RMS bunchlength of 0.4 mm from the gun. (See Fig. 3.) Both 1-D and 3-D CSR tracking [10] have been done to calibrate the resistive wake model and investigate CSR and space charge effects on transverse emittance. Heating the uncompressed bunches by a laser heater so that the energy spread is 5-10 keV is predicted to suppress longitudinal microbunching instability for initial wavelengths less than ~100 μm.

To ensure successful overlap of the seed laser with the 200 pC electron bunch the arrival-time jitter of the beam must be <15 fs RMS. Sensitivity calculations indicate that the amplitude and phase stability of the injector linac cavity fields must be less than 0.01% and 0.02º RMS respectively, under the assumption of uncorrelated errors. This performance level is at the current state of the art in control of superconducting cavities.

BEAM SWITCHYARD

The desire to run independent beams at repetition rates ranging from Hz to hundreds of kHz requires a beam distribution system based on RF separation. In order to make separation practical the separator cavities must provide a total kick of ~2 mrad. Two existing structures appear suitable [11, 12].

The beam separation system consists of a two level binary tree with three separator stages. Four beam ports are possible at each energy. The low energy pickoff point requires another separator with a larger separation angle in order to avoid interference between the high and low energy beamlines. The beams are bent symmetrically giving the minimum bend to each beam for a given separation angle.

Separation is accomplished using the conventional technique of amplifying the RF kick by a downstream defocusing quadrupole. The beams are separated into individual paths using a double septum dipole. Creating a pseudo double bend achromat structure using another dipole closes the dispersion bump and further increases the separation angle. This arrangement gives relatively low horizontal beta functions in the bends, which is desirable for CSR considerations.

The use of RF separation restricts the beam structure in the accelerator to a periodic sequence of frames consisting

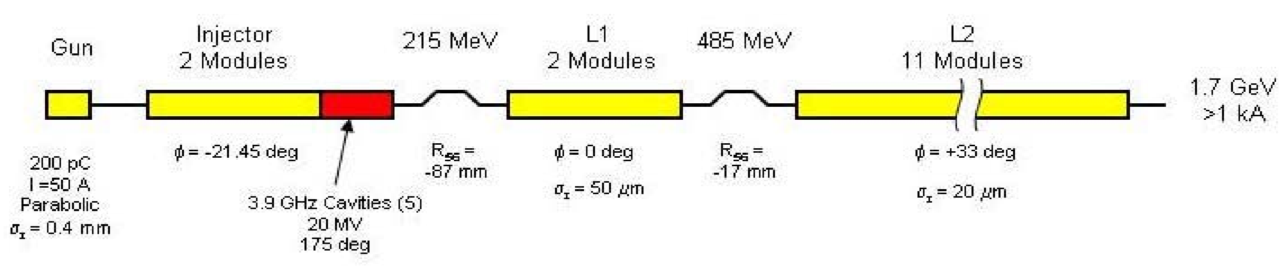

Figure 2: Possible linac layout, including bunch compressors.

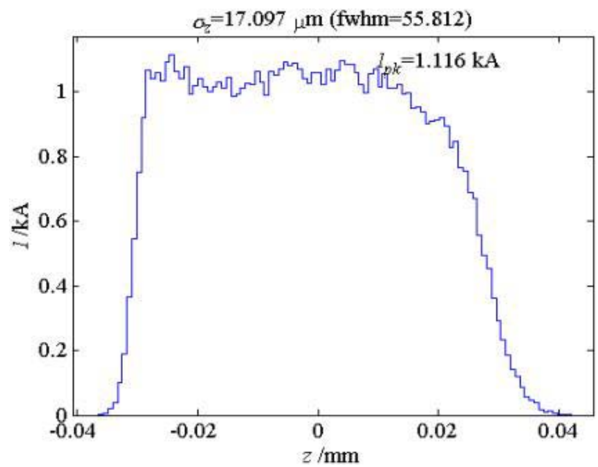

Figure 3: Current along the electron bunch at 1.7 GeV.

of individual time slots for each beamline. Choosing whether its time slot is filled in any given frame, via the photocathode drive laser, controls the repetition rate of a particular beamline. Eight time slots in a frame means that the maximum repetition rate of a beamline is one eighth of the maximum linac bunch rate. The rate of each beamline is independently adjustable to any submultiple of the maximum rate.

TIMING SYSTEMS

The gun and seeding lasers require synchronization to 10s of femtoseconds in order to minimize the electron bunch length required to ensure overlap between the electron bunch and the seed laser pulse. The RF system and User probe lasers will also need to be synchronized with the gun and seed lasers to comparable precision. In collaboration with MIT, DESY and FERMI, such a timing distribution system has been developed over the last few years [13, 14]. First deployment and test of this system is under way at the VUV-FEL FLASH at DESY [15] and FERMI at ELETTRA.

A layout of the synchronization system for a generic seeded FEL facility as discussed for the current project is shown in Fig. 4. An optical master oscillator in the form of a mode-locked laser has a pulse repetition rate tightly synchronized to an ultra low noise microwave oscillator [15], which times the overall facility.

The pulses from the optical master oscillator, with about 100 fs duration and a few hundred MHz repetition rate, are distributed via timing stabilized and dispersion compensated optical fiber links to all locations where precise optical and RF signals are needed or diagnosed. The fiber links are stabilized via partial back reflection of the pulse stream to the source and cross correlation with the following pulses from the laser [14]. Low-jitter RF-signals are extracted at the end of the link using balanced optical-RF phase detectors. At this point, ultra low jitter fiber lasers with 200 MHz repetition rate have been demonstrated [13] suitable to serve as optical master oscillator. Fiber links with 300 m length have been built

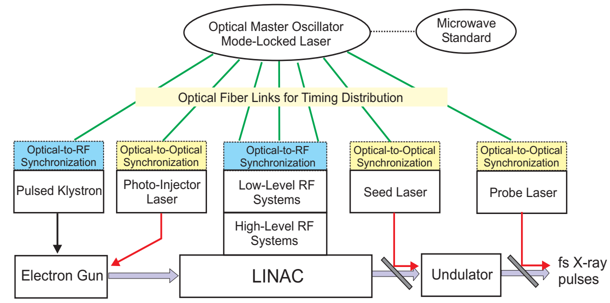

Figure 4: Schematic outline of the timing distribution and synchronization for the FEL facility.

and tested. They are long term stable with only <10 fs jitter and drift over 100 s. The time duration was only limited by the servo length of the fiber stretcher used. This limitation can easily be extended to arbitrary durations. Long term stable RF-extraction of 10 GHz signals from the optical pulse stream has also been demonstrated with less than 50 fs jitter and drift over one hour. These preliminary system demonstrations show that a highly robust, long term stable optical and RF-timing distribution system with <10 fs jitter over hundreds of meters can be accomplished with moderate additional R&D effort. The system proposed here involves only a single mode-locked laser source. This can be easily laid out as a twin-system to achieve redundancy of the only critical system component, which should lead to 100% reliability of the timing distribution system.

REFERENCES

[1] J. Bisognano *et al.*, “The Wisconsin VUV/Soft X-ray Free Electron Laser Project”, these proceedings.
[2] W. Graves *et al.*, “Wisconsin XFEL Source Properties: Optimization for Science Applications”, these proceedings.
[3] C. Limborg-Deprey, P. Bolton, *NIM-A*, 557 pp. 106-116 (2006).
[4] O.J. Lutein *et al.*, *Phys. Rev. Lett.*, **93**, 094802-1 (2004).
[5] D. Janssen *et al.*, EPAC 2006, pp. 2469-2471.
[6] K. Flottmann, http://www.desy.de/~mpyflo/.
[7] F. Marhauser, EuroFEL WP5 Collaboration Meeting on Simulation Results, June 2-3, 2005, BESSY Berlin.
[8] L. Harwood, LINAC 2006, pp. 70-72.
[9] K.L.F. Bane and P. Emma, PAC 2005, pp. 4266-4268.
[10] M. Dohlus and T. Limberg, FEL 2004, pp. 18-21.
[11] C. Leeman, G. Yao, LINAC 1990, pp. 232-234.
[12] Yu. Senichev *et al.*, PRST-AB 9, 012001 (2006)
[13] J. Chen *et al.*, Opt. Lett. 32:(11), pp. 1566-1569 (2007).
[14] J Kim *et al.*, Opt. Lett. 32:(9), pp. 1044-1046 (2007).
[15] F. Loehl *et al.*, “First prototype of an optical cross-correlation based fiber-link stabilization for the FLASH synchronization system,” DIPAC 2007.