STUDIES OF A LINAC DRIVER FOR A HIGH REPETITION RATE X-RAY FEL*

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Abstract

We report on on-going studies of a superconducting CW linac driver intended to support a high repetition rate FEL operating in the soft x-rays spectrum. We present a point-design for a 1.8 GeV machine tuned for 300 pC bunches and delivering low-emittance, low-energy spread beams as needed for the SASE and seeded beamlines.

INTRODUCTION

A concept of high-repetition rate FEL machine generating soft x-rays in the 1 nm range is currently under study at LBNL. Here we discuss a possible point-design for the SCRF, CW linac-driver of the machine capable of supporting the FEL performance as outlined in Ref. [1], and focus on single-bunch aspects of beam dynamics. This is part of a continuing exploration aiming at finding an eventual optimal design solution. For this study we targeted the following set of beam parameters at the FEL: 0.6 μm normalized slice transverse emittance, 50-60 keV uncorrelated rms energy spread, and 500 A or higher current (see Table 1). These values follow from consideration of the beam quality out of the injector, the requirements for lasing, and general trade-offs affecting the electron brightness. The relatively low current is dictated by the need of a small uncorrelated energy spread in the seeded FEL beamlines (implying modest bunch compression and minimization of collective effects). The lower limit to the length of the high-quality beam core is determined by the two-color FEL beamline [2] and desired level of radiation output from the other two beamlines. In particular, the requirement to have up to 150 fs delay between the two seeding laser pulses and a safety margin against time-jitter estimated to be ±50 fs implies a need for at least a 250 fs duration for the usable beam core. A conservative allowance for up to half of the total bunch charge to reside within the unusable portion of the beam would then implies a total bunch charge of 250 pC or larger. For the present study we assumed a 300 pC charge/bunch, consistent with the desired small normalized transverse emittance obtainable from the injector [3]. Given the 30-50 A range for the beam peak current expected out of the injector, a 10-17 compression factor is required of the linac. The beam dynamics studies presented in the following were carried using idealized (e.g. Gaussian) electron bunches at injection with basic properties (peak current, emittance, and energy spread) that reproduce those from the injector. Further studies will include full start-to-end beam dynamics simulations and design optimization of the integrated injector and linac systems.

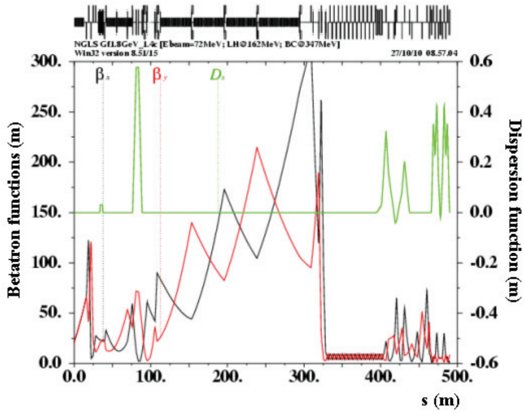

Figure 1: Lattice functions through the linac and the spreader including transport to one of the beamlines.

MACHINE LAYOUT

The linac driver is designed to accept electron bunches at about 70 MeV energy from the injector and provide acceleration up to 1.8 GeV before directing the beam to the spreader for distribution into separate FEL undulator lines. This value of beam energy, still tentative, sits at the low-end of a range permitted by available undulator technology and is likely have to be increased for optimal performance. The proposed layout, based on the preliminary choice of TESLA-like superconducting cavity technology, includes components that have become conventional in existing or proposed 4th-generation light sources. The linac consists of six main sections (for a schematic see Fig. 1 in [1]). The first section, Linac 0, interfaces the linac with the injector, provides about 90 MeV acceleration, and accommodates the diagnostics stations needed to monitor the beam phase space before the "laser heater". The beam is then further accelerated in Linac 1 (with 225 MeV energy gain), conditioned by passage through a 3.9 GHz third-harmonic RF structure, compressed through a single-chicane bunch compressor (BC) at about 350 MeV energy, and then accelerated to the final energy by Linac 2, the last linac section. Following the linac, fast kickers placed along the spreader distribute the beam to multiple beamlines. The lattice func-

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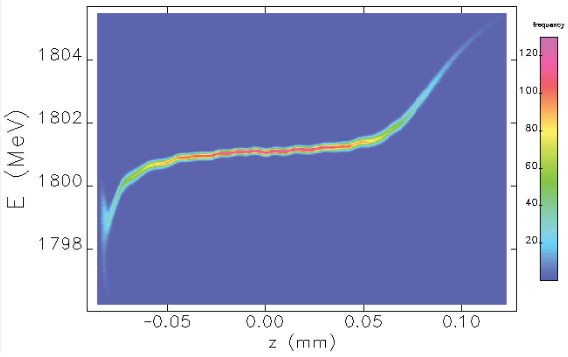

Figure 2: Longitudinal phase-space at the exit of the spreader (Elegant simulations).

tions through the linac, the spreader, and one of the beamlines up to the undulators are shown in Fig. 1. The lattice is a close variant of an earlier concept of a 2.4 GeV linac driver considered previously [4].

DESIGN CONSIDERATIONS

The desire to minimize the microbunching instability is the main motivation for our preference to have a single-chicane BC in the lattice. The microbunching instability can increase the uncorrelated energy spread beyond a level tolerable for efficient application of laser seeding, and previous studies have shown that the instability can be substantially amplified by passage through multiple chicanes. The magnitude of the amplification, however, is also critically dependent on the beam current, and a final choice of an optimal lattice design will have to further revisit the benefits (such as reduced sensitivity to beam timing jitter and more control over the beam energy chirp) of a multiple-chicane BC. Additional BCs may become necessary if integrated injector/linace studies will indicate a need to modify the balance in favor of more compression occurring in the linac versus that performed at lower energy in the injector (velocity bunching). The choice of beam energy at the BC should aim at reducing the impact of CSR on the horizontal emittance (which scales inversely with the beam energy), but faces other trade-offs. A lower beam energy would be favored, among other reasons, by consideration of the microbunching instability (a lower energy would increase longitudinal phase-space mixing and reduce the impact of LSC forces, as a lower-energy chicane would reduce the beam time-of-flight between the injector and the chicane). The value adopted here, 350 MeV, appears to strike an adequate balance between these competing requirements. Further containment of CSR effects can be accomplished by careful lattice design aiming at minimizing the dispersion invariant function in the end region of the chicane. The adopted design is a conventional four-bend, C-shaped, 12.64 m long chicane with $R_{56} = -0.135$ m.

A degree of control over the microbunching instability is offered by the use of a laser heater – essentially an inverse FEL consisting of a wiggler inserted in a small, dedicated chicane. A conventional laser pulse interacts with the beam in the wiggler and induces an energy modulation (at a wavelength equal to that of the laser), which by the exit of the chicane is effectively converted into an uncorrelated energy spread. As the development of microbunching is sensitive to the uncorrelated energy spread, proper tuning of the laser pulse power allows for an effective control of the instability. The proposed laser heater located at about the point of 160 MeV beam energy is similar to the LCLS design. A laser pulse, sufficiently long to accommodate the electron bunch and carrying a few μjoules of energy, will suffice to induce the few-keV energy spread that our studies indicate are needed to stabilize the beam. An essential component of the machine layout is a higher harmonic RF structure needed to linearize the longitudinal phase space before the BC. A third harmonic (3.9 GHz), RF structure modeled after the one recently installed at FLASH [5], with 5 MeV maximal energy per cavity but with 7 or perhaps 9 cavities instead of the 4 cavities of the FLASH linearizer, represents a natural choice. Beam dynamics simulations point to a voltage requirement on the order of 35 MV.

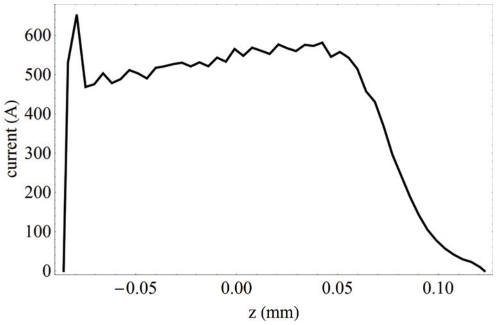

Figure 3: Longitudinal density at the exit of the spreader (Elegant simulations). Bunch head is at $z < 0$.

Table 1: Selected Beam Parameters at the FEL

Energy	1.8 GeV
Length of usable beam core	250 fs
Transverse slice emittance $\gamma\varepsilon_\perp$	0.6 μm
Uncorr. energy spread	60 keV
Charge/bunch	300 pC
Current	500 A

BEAM DYNAMICS

We studied three important aspects of beam dynamics: the evolution of the long-scale features of the longitudinal phase space, CSR-induced emittance growth, and the microbunching instability. We evaluated the first two effects with the code Elegant [6] using a relatively small (but for this purpose adequate) number of macroparticles (up to 400k), whereas we employed the IMPACT code's capabilities for high resolution, billion-macroparticle simulations

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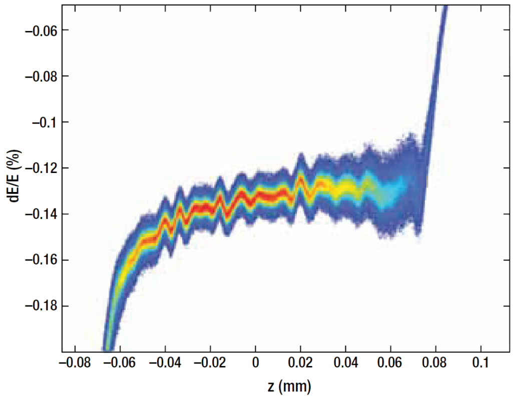

Figure 4: The beam longitudinal phase space as simulated by IMPACT (including long. space charge) shows evidence of microbunching instability but the effect is small.

to address the microbunching instability [7], which is notoriously sensitive to spurious noise induced by a small population of macroparticles. In both cases we assumed at the linac injection a beam with Gaussian density truncated at about 3σ in the full 6D phase space (1.8σ in z in the IMPACT simulations), 40 A peak current, and 0.6 μm normalized transverse rms emittance. The linac was set to generate about a 13-fold compression to achieve the desired peak current (∼500 A) at extraction. The linac setting was determined, in first approximation, using a *Mathematica* script [9] including RF field and RF structure wakefield effects, and then empirically fine-tuned using the macroparticle simulation codes. The Elegant simulations included the short-range longitudinal RF wakefields, employing available models for the TESLA-like cavities [8], CSR (1D model), but not longitudinal space-charge effects (to avoid amplification of artificial instabilities caused by the limited number of macroparticles), whereas the IMPACT simulations included full longitudinal and transverse space-charge modeling as well. The IMPACT simulations were carried out with one billion macroparticles (only about a factor of two smaller than the actual electron bunch population). Both the Elegant (Fig. 2 and 3) and IMPACT (Fig. 4) simulations show that the initial Gaussian bunch transforms along the linac into a bunch with a relatively flat density in the core, primarily as a result of the cubic term in the longitudinal RF wakefields generated in the RF structures before the BC. The beam energy chirp beyond the BC is partially offset by the RF wakes in Linac 2, but complete removal of the chirp requires operating Linac 2 off crest by about 25 degrees. The Elegant simulations show a CSR induced projected emittance growth to 0.76 μm over the entire bunch and to 0.63 μm over the useful core of the beam (with the slice emittance in the beam core remaining about unchanged at 0.6 μm).

A slightly higher compression would be possible but at the expense of the appearance of current spikes along the bunch. For an ideal parabolic bunch with rms length σ_z (and assuming exact removal of the quadratic term in the beam energy chirp by the linearizer) it can be shown [9] that the maximum allowed compression before this happens scales as $C_{\rm crit} = 1/(15|h_3 R_{56}|\sigma_z)$ where h_3 is the third-order term of the energy chirp induced by the RF wakefields in the structures preceding the BC. Decreasing $|R_{56}|$ in the BC would in principle allow for a larger $C_{\rm crit}$ but would aggravate the task of removing the energy chirp past the BC (as a smaller $|R_{56}|$ requires more energy chirp for a given compression factor).

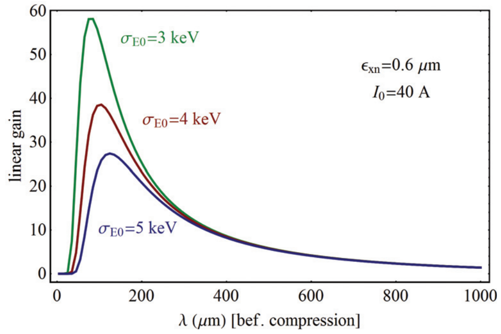

Figure 5: Linear gain for the microbunching instability through the bunch compressor as a function of the charge-density modulation wavelength before compression.

IMPACT runs, taking into full account LSC effects, were repeated for various values of the uncorrelated energy spread of the input bunch, meant to model different settings of the laser heater. We found that a beam with an initial $\sigma_{E0} = 4$ keV uncorrelated rms energy spread is scarcely affected by the microbunching instability seeded by the beam shot-noise (see Fig. 4), and that the resulting energy spread at the end of the linac remains close to the value expected from ideal compression (i.e., ∼60 keV). The small energy modulation observed is about consistent with the prediction from the linear theory showing moderate gain for the instability, Fig. 5. The gain peaks at a (compressed) wavelength $\simeq 8\mu$m, also consistent with the wavelength of the small energy modulation seen in Fig. 4.

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