FEASIBILITY STUDIES FOR ECHO-ENABLED HARMONIC GENERATION ON CLARA

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Abstract

The Compact Linear Accelerator for Research and Applications (CLARA) is a proposed single-pass FEL test facility, designed to facilitate experimental studies of advanced FEL techniques applicable to the next generation of light source facilities. One such scheme under consideration is Echo-Enabled Harmonic Generation (EEHG). In this paper we explore the suitability of CLARA for carrying out studies of this scheme, combining analytical and numerical calculations to determine likely hardware operating ranges, parameters tolerances and estimated FEL performance. A possible adaptation to convert EEHG into a short-pulse scheme is also considered.

INTRODUCTION

The Compact Linear Accelerator for Research and Applications (CLARA) is a proposed single-pass FEL test facility, the primary purpose of which is to provide a location where advanced FEL techniques can be studied experimentally [1]. The layout for CLARA has been designed to be flexible, with a range of possible experiments considered from an early stage.

The main focus of CLARA is the production of ultra-short pulses of coherent light. Alongside this, there are a large number of other topics of interest, such as novel schemes to improve the FEL intensity and wavelength stability, methods to improve the longitudinal coherence, and demonstrating higher harmonic radiation from bunches conditioned by an external laser seed source.

Echo-Enabled Harmonic Generation (EEHG) [2, 3] is one of the techniques that has been studied explicitly for CLARA. This scheme requires two energy modulation plus chicane stages to be installed upstream of the main radiator section. These are used to induce a fine-structure density modulation in the electron bunch before it passes through the radiators, and so the specifications for these components must be compatible with the requirements for the EEHG scheme. Similarly, it is important to quantify in advance what the spectral and temporal FEL pulse characteristics are likely to be in order to inform the choice of photon diagnostics to be installed on CLARA. It is also important to establish at an early stage whether there are any limiting effects that may prevent successful demonstration of the scheme on CLARA. For example, incoherent synchrotron radiation (ISR) emission in the first chicane could increase the energy spread and blur out the fine-structure energy bands present in the beam. This may not be an issue for CLARA because of the relatively low beam energy. Alternatively, the EEHG-induced micro-bunching could lead to significant coherent synchrotron radiation (CSR) emission in the second chicane, particularly in the final dipole. The bunching could be degraded by R_{51} leakage from the chicanes, by space-charge (SC) or intra-beam scattering (IBS) effects, or during beam transport to the FEL due to the finite beam emittance and energy spread. All of these issues can be investigated in advance using sophisticated particle tracking and FEL simulation codes.

Table 1: Simulated Electron Bunch Parameters at FEL

Parameter	Value
Charge (pC)	250
Energy (MeV)	228
RMS Pulse length (fs)	250
Peak current (A)	400
Normalized emittance (mm.mrad)	0.6
Energy Spread (keV)	75

In this paper we summarise the studies that have been made for EEHG on CLARA, starting with the analytical calculations used to determine likely hardware operating ranges and parameter tolerances. These are supplemented by in-depth numerical simulations of the standard EEHG configuration, followed by preliminary studies of a possible adaptation of EEHG to a short-pulse generation scheme.

ANALYTICAL STUDIES

CLARA Parameters

The main CLARA linac consists of an S-band, normal conducting linac, combined with an X-band 4$^{\text{th}}$ harmonic linearising RF cavity and standard C-type bunch compressor [1]. Depending upon the particular experimental requirements, several different operating modes are foreseen for the main linac, including ‘SASE’ (short bunch), ‘seeded’ (long bunch), ‘single-spike’, ‘multi-bunch’ and ‘industrial applications’ modes. For EEHG, it is anticipated the linac will be run in the seeded mode, for which the accelerator working point is optimised to produce a flat-top current profile. This is intended to minimise the sensitiv-

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Table 2: Summary of EEHG Parameter Ranges

	h	$\lambda_{bunching}$ (nm)	A_1	A_2	B_1	B_2	b_{nm}	$E_L^{(1)}$ (μJ)	$E_L^{(2)}$ (μJ)	$R_{56}^{(1)}$ (mm)	$R_{56}^{(2)}$ (mm)
	8	100	3	1	11.22	1.34	0.155	6.42	0.71	4.34	0.52
	8	100	3	3	4.09	0.45	0.155	6.42	6.42	1.58	0.17
	8	100	5	3	3.91	0.45	0.171	17.83	6.42	1.51	0.17
	40	20	3	1	44.32	1.09	0.095	6.42	0.71	17.16	0.42
Nominal Electron Bunch	40	20	3	3	15.13	0.36	0.095	6.42	6.42	5.86	0.14
	40	20	5	3	14.95	0.36	0.105	17.83	6.42	5.79	0.14
	100	8	3	1	105.3	1.05	0.071	6.42	0.71	40.76	0.41
	100	8	3	3	35.46	0.35	0.071	6.42	6.42	13.72	0.14
	100	8	5	3	35.27	0.35	0.078	17.83	6.42	13.65	0.14
	8	100	3	1	11.22	1.34	0.155	26.81	2.98	2.17	0.26
	8	100	3	3	4.09	0.45	0.155	26.81	26.81	0.79	0.09
	8	100	5	3	3.91	0.45	0.171	74.48	26.81	0.76	0.09
	40	20	3	1	44.32	1.09	0.095	26.81	2.98	8.58	0.21
Degraded Electron Bunch	40	20	3	3	15.13	0.36	0.095	26.81	26.81	2.93	0.07
	40	20	5	3	14.95	0.36	0.105	74.48	26.81	2.89	0.07
	100	8	3	1	105.3	1.05	0.071	26.81	2.98	20.38	0.20
	100	8	3	3	35.46	0.35	0.071	26.81	26.81	6.86	0.07
	100	8	5	3	35.27	0.35	0.078	74.48	26.81	6.83	0.07

ity to temporal jitter between the electron bunch and seed lasers; however, for the present study a Gaussian bunch distribution has been assumed. The main electron bunch parameters used here are listed in Table 1.

For the EEHG calculations, both modulators were taken to be 0.975 m long with 65 mm period, set to be resonant at the seed laser wavelength of 800 nm (K_U = 2.793). The radiators were modelled as 2.484 m long devices with period 27 mm. With these parameters and electron bunch energy, the shortest wavelength at which FEL gain could be demonstrated is 100 nm (assuming a minimum undulator parameter of K_U = 1). This corresponds to EEHG operating at the 8th harmonic of the proposed seed lasers.

The modulators and radiators lie within a FODO channel with 3.5m quadrupole to quadrupole separation, with additional quadrupoles either side of the chicanes to assist in matching the Twiss parameter along the line. This FODO period allows sufficient room for a 4-dipole C-type chicane to be installed downstream of each modulator, with the length of the dipoles and the dipole separation all set to 0.22 m. A plot showing the Twiss parameters matched for the EEHG scheme operating at the 8th harmonic is shown in Fig. 1. Note that the above parameters represent the machine layout at an early stage of the design process and have now been superseded [1].

EEHG at the 8th Harmonic

The performance of EEHG on CLARA was first studied using the analytic equations of [3] for a range of possible scenarios. In each case, the bunching factor at the entrance to the first radiator was calculated, and the scaled parameters used in [3] were converted into hardware parameters using standard analytic equations. The calculations were

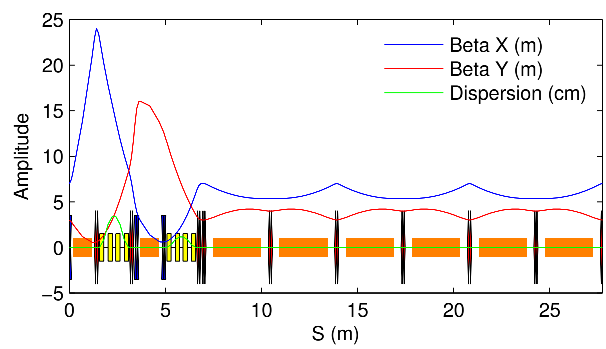

Figure 1: Optical functions through the modulator and radiator sections. Note that each quadrupole has been split into two to allow optical functions to be calculated at the magnet centres.

carried out twice, once using the nominal electron bunch parameters given in Table 1, and then using degraded electron bunch parameters of ϵ_N = 1 mm.mrad and σ_E = 150 keV. The results of these are given in Table 2. For all these calculations, the modulating laser pulse duration was taken to be 500 fs rms, and the laser spot size calculated assuming an optimum Rayleigh length of half the modulator length.

Tolerance Estimates

A quick estimate of the tolerances on laser pulse energy and chicane magnet field strength was made by scanning the amplitude of each variable and calculating the bunching at 100 nm. This is shown in Fig. 2, in which the chicane strengths were first varied at fixed laser pulse energy (left image), then the laser pulse energies were varied at fixed chicane strength (right image). From this, it appears a tol-

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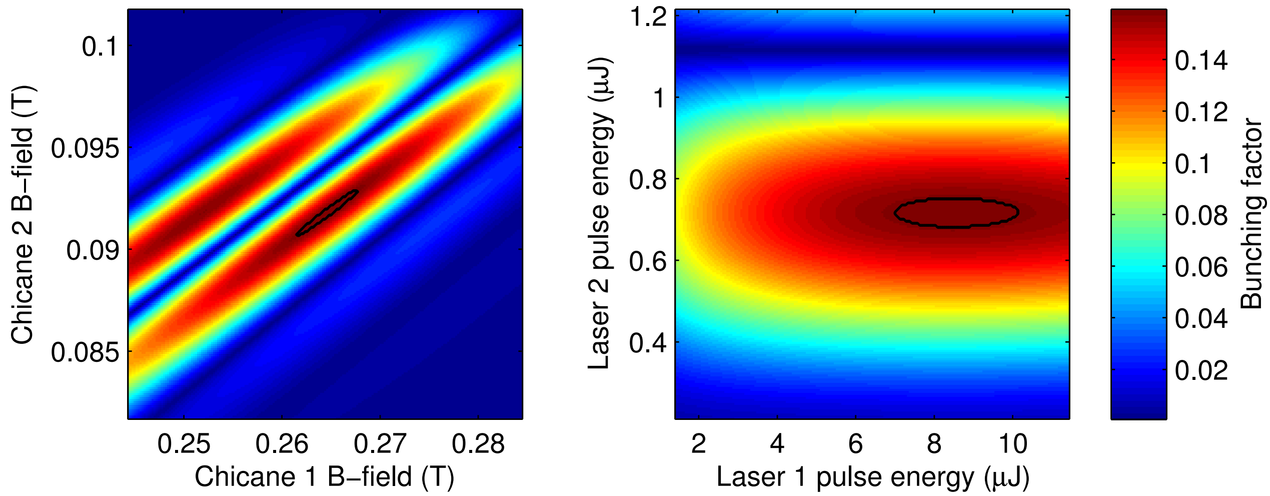

Figure 2: Bunching factor calculated as a function of field strength for the two sets of chicane magnets (left) and laser pulse energy (right). The black contours highlight the region where the bunching is within 1% of maximum.

erance of around ± 0.035 μJ for the laser 2 pulse energy, and around ± 0.25 mT for the chicane B-fields would be required to maintain bunching at within 1% of maximum.

These tolerances become tighter when operating at higher harmonics of the seed laser. For example, the tolerance on laser 2 becomes ± 0.012 μJ for h = 40 (20 nm bunching) and ± 0.007 μJ for h = 100 (8 nm bunching).

PARTICLE TRACKING STUDIES

EEHG at the 8th Harmonic

One of the key features of EEHG is the strong chicane strength required to induce the initial energy bands in the longitudinal phase space. To accommodate this, the code used to simulate the modulator and chicane stages must allow particles to be able to migrate from one longitudinal slice to another. In addition, the code should include dynamic effects such as ISR, CSR and SC, and take into account the higher order terms in the beam transport equations. In this study, ELEGANT [4] has been used to simulate the EEHG process up to the entrance of the radiators.

Another important consideration lies in correctly accounting for shot-noise in the electron bunch when modelling the FEL gain. GENESIS [5] contains an algorithm to re-distribute the longitudinal coordinates of particles loaded from an external file that gives the correct bunching statistics when using a reduced number of macro-particles for a randomly-distributed electron bunch. However, this would remove the (correct) bunching introduced by the EEHG scheme. As an alternative, the shot-noise algorithm can be by-passed, but using a reduced number of macro-particles in the simulation could distort the statistics and artificially enhance the bunching factor, jump-starting the SASE process. The latest version of GENESIS [6] does however provide the facility to track individual electrons. Using this option, the initial bunching statistics are guaranteed to be correct for both EEHG and pure SASE simulations.

The final tracking procedure adopted was as follows:

- Use GENESIS to create an initial particle distribution, with the number of macro particles equal to the number of electrons in the bunch
- Convert the GENESIS distribution into a binary SDDS ELEGANT input file
- Track the distribution through the two modulator and chicane sections using ELEGANT
- Convert the ELEGANT output into an HDF5-format PARTFILE and import into GENESIS
- Simulate the FEL process using GENESIS

For the ELEGANT simulations, a 74 μm (250 fs) long portion of the electron bunch was created, containing a total of 591 million particles (~830K particles per slice for 400 A peak current and 100 nm wavelength). After cutting the tails of the distribution, this was reduced to 64 μm when imported to GENESIS. The energy modulation was simulated using the LASERMODULATOR element in ELEGANT, with the laser pulse energies kept fixed at the values quoted in Table 2. To ensure optimal bunching, a scan was carried out for the chicane bend angles, resulting in final values of 0.265 T and 0.090 T for chicanes 1 and 2 respectively, compared with the analytic values of 0.264 T and 0.092 T. The tracking was carried out twice; once with ISR and CSR effects in the bending magnets disabled, and once with them included. The phase space coordinates after the two modulators and chicane sections are shown in Fig. 3 for the case where CSR and ISR were included.

The results of the GENESIS simulations are summarised in Fig. 4. From these, the following conclusions can be drawn. Firstly, the parameter settings identified during the analytic studies of the previous section are indeed good enough to provide an initial bunching of >0.15 depending upon the slice, even when ISR and CSR effects are included in the tracking. This initial bunching results in the EEHG

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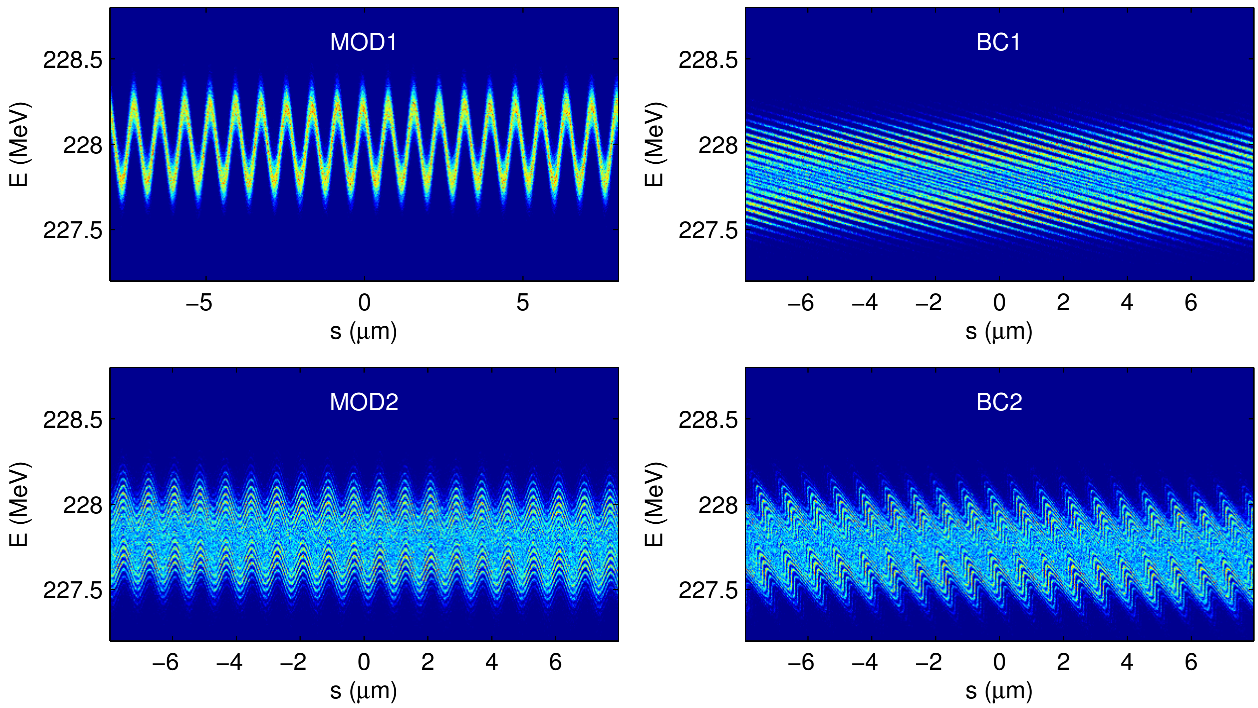

Figure 3: Electron beam phase space after the first modulator (top left), first chicane (top right), second modulator (bottom left) and second chicane (bottom right). CSR and ISR effects were included.

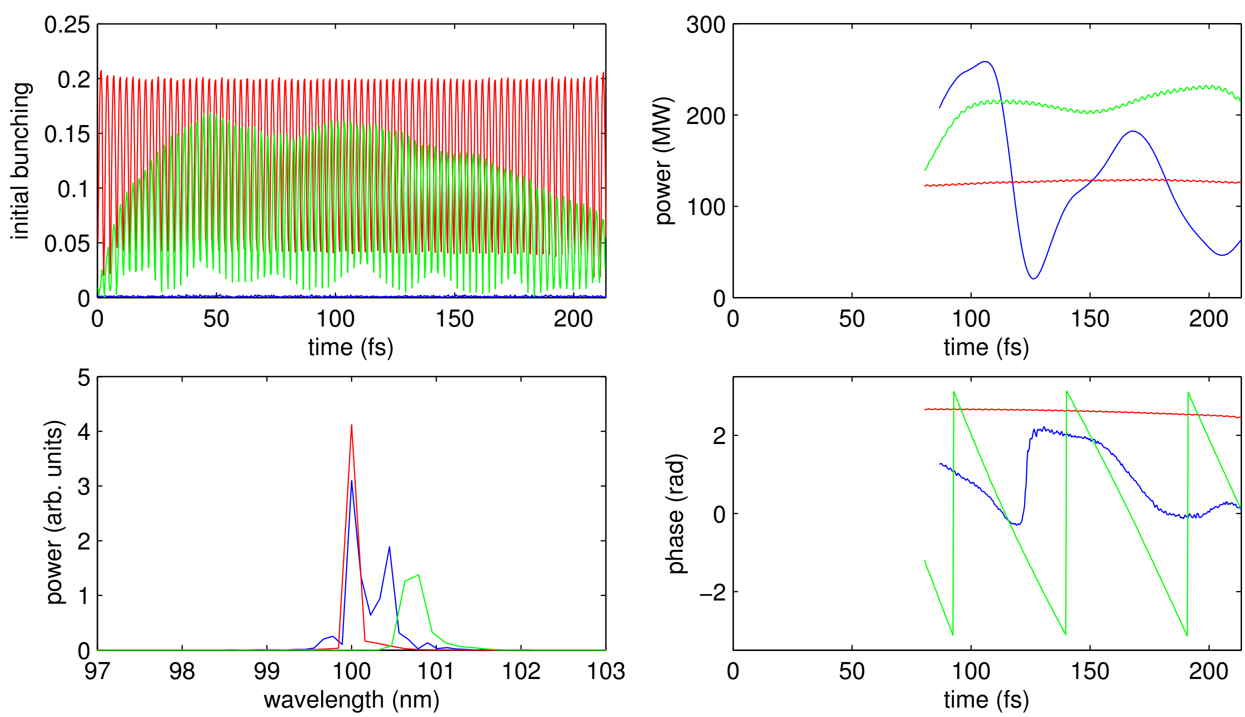

Figure 4: Summary of electron beam and radiation properties. Shown are the cases for a pure SASE simulation (blue), EEHG (red) and EEHG including ISR and CSR effects in the chicanes (green).

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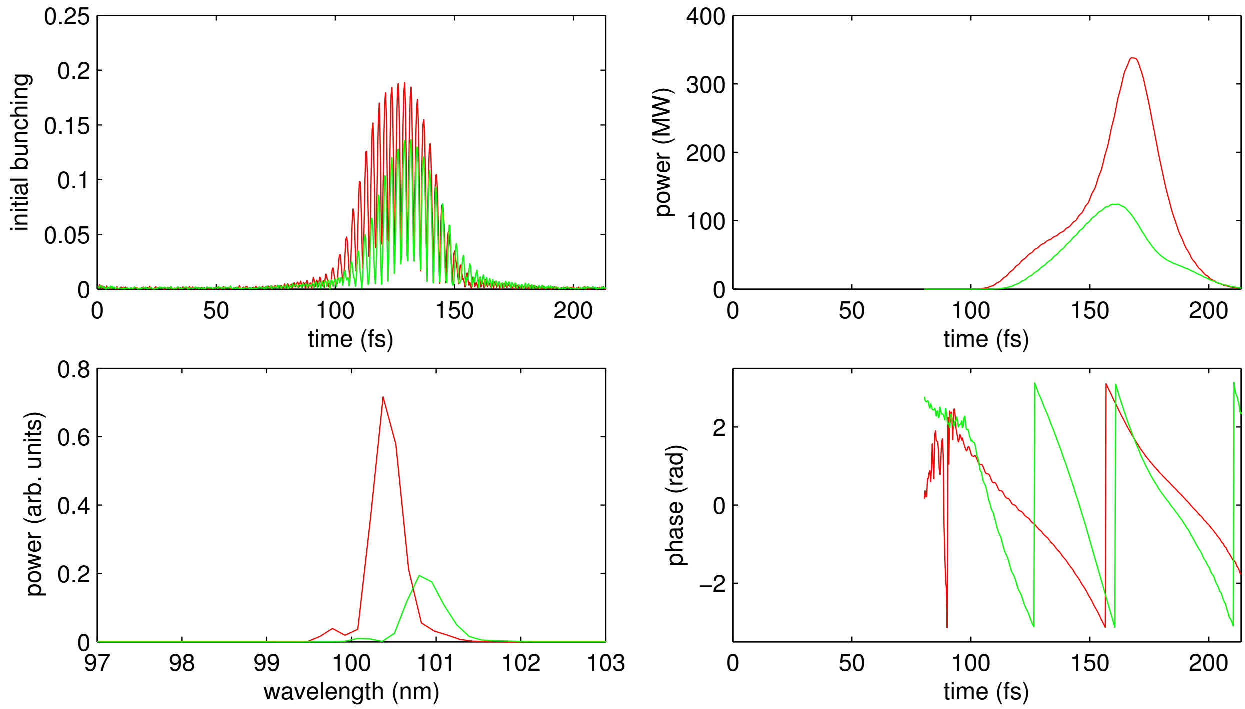

Figure 5: Summary of electron beam and radiation properties for EEHG as a short pulse scheme. Shown are the cases for EEHG (red) and EEHG including ISR and CSR effects in the chicanes (green).

FEL reaching saturation after two radiator modules (6.5m) compared with 4 modules (13.5m) for the SASE case. The saturation power is comparable for the three cases considered at 100-200 MW; however, the temporal coherence is clearly higher for the EEHG pulses than the SASE case. This can be seen primarily in the radiation phase at saturation. The bandwidth of the EEHG pulses is narrower than the SASE pulse, displaying a single spike in the spectral profile compared with the two spikes visible in the SASE pulse. Note ISR and CSR introduce an energy offset and chirp to the electron beam causing the resonant wavelength to be slightly offset. It is this wavelength offset that causes the apparent phase advance for the radiation phase at saturation shown in Fig. 4.

EEHG as a Short Pulse Scheme

The main objective for the CLARA project is to demonstrate the generation of stable, synchronised, ultra-short pulses of coherent light. The most straight-forward way to fulfil this aim using an EEHG scheme is to replace the second modulating laser with a shorter laser pulse, as this limits the portion of the bunch that contains the correct density modulation when entering the radiator. To study this, the laser pulse for the second modulator was replaced with one of 40 fs FWHM duration. The pulse energy was reduced from 0.71 μJ to 24.1 nJ to maintain the same energy modulation amplitude. The results of the GENESIS simulations are shown in Fig. 5.

As with the standard EEHG simulations, the initial bunching at the entrance to the radiator section is ~0.15, even when ISR and CSR are included. This results in a steep initial rise in peak power in the first radiator module, reaching 100-300 MW after the second module. The FEL pulse duration at 6.5 m into the radiator is 26.4 fs FWHM neglecting ISR and CSR effects, and 37.4 fs with them included. Both FEL pulses still contain a single spike in the frequency domain, although the line-widths have broadened compared to the standard EEHG cases. The longitudinal coherence is again high, as shown by the uniform radiation phase advance at saturation.

CONCLUSIONS

A combination of analytic and numerical studies have been used to study the implementation of EEHG on CLARA. The likely operating ranges and tolerances of the various hardware components appear feasible, and no limiting effects have been identified that could prevent successful demonstration of the scheme on CLARA, either in standard or in short-pulse configurations.

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