DESIGN OF A 10-MHz HIGH-ENERGY-RESOLUTION LIGHT SOURCE

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Abstract

High energy resolution is essential for advanced spectroscopic studies of quantum materials, especially for resolving low-energy electronic features in angle-resolved photoemission spectroscopy (ARPES). However, existing light sources for ARPES still face difficulties in simultaneously providing narrow bandwidth and high photon flux. We are developing a 10-MHz coherent light source based on angular-dispersion-induced microbunching (ADM), aiming to generate narrow-band radiation with sub-meV-level energy resolution. Start-to-end simulations from the injector to the radiator have been performed to evaluate the beam dynamics and radiation performance. The simulation results show that the proposed source can provide sub-meV-level energy resolution and a photon flux above 10^{12} photons/s over a broad photon-energy range.

INTRODUCTION

Angle-resolved photoemission spectroscopy (ARPES) is a central technique for resolving the electronic band structure of quantum materials [1]. Recent studies of subtle electronic features, such as superconducting gaps and Dirac-cone dispersions, require higher spectral resolution and better photon statistics. Since photons in the 10–100 eV range are particularly useful for valence-band and Fermi-surface measurements, a source providing sub-meV-level bandwidth and sufficient photon flux over this range is highly desirable. Moreover, for a given average photon flux, a higher repetition rate reduces the photons per pulse, helping to mitigate space-charge effects and improve measurement stability.

Although existing light sources used for ARPES have achieved impressive performance, they still involve trade-offs among energy resolution, photon flux, and spectral coverage. Laser-based systems provide excellent energy resolution at low photon energies but have limited photon-energy tunability, whereas synchrotron beamlines offer broad spectral coverage but cannot easily reach sub-meV-level bandwidth without a substantial loss of photon flux.

In this work, we propose a 10-MHz coherent light source based on angular-dispersion-induced microbunching (ADM) [2], using a 550-MeV electron beam. In this scheme, the electron-beam energy is correlated with the transverse divergence before the modulator, which mitigates the impact of initial energy spread on high-harmonic microbunching. As a result, ADM can reduce the required seed-laser power by two to three orders of magnitude compared with conventional coherent harmonic generation (CHG) [3]. The proposed source aims to provide narrow-band radiation with sub-meV energy resolution, high photon flux, and broad photon-energy coverage.

LAYOUT

The layout of the proposed scheme is shown in Fig. 1. This facility consists of an injector, a linac, and a downstream ADM section. The electron gun design follows the SHINE injector scheme [4]. A VHF gun generates 10 MHz, 10 pC electron bunches with a pulse duration of 20 ps, corresponding to an average current of 0.1 mA. The beam is focused by solenoids and accelerated by a single 9-cell superconducting cavity followed by an injector 8-cavity cryomodule (i8CM), reaching an injector exit energy of 130 MeV.

The main linac consists of one 3.9 GHz cryomodule and three 1.3 GHz accelerating cryomodules, boosting the beam energy from 130 MeV to 550 MeV. At the linac exit, the normalized emittance and relative energy spread are about 0.15 mm·mrad and 0.01%, respectively. Three-dimensional start-to-end (S2E) simulations have been carried out using *ASTRA* and *ELEGANT* for injection and acceleration [5,6].

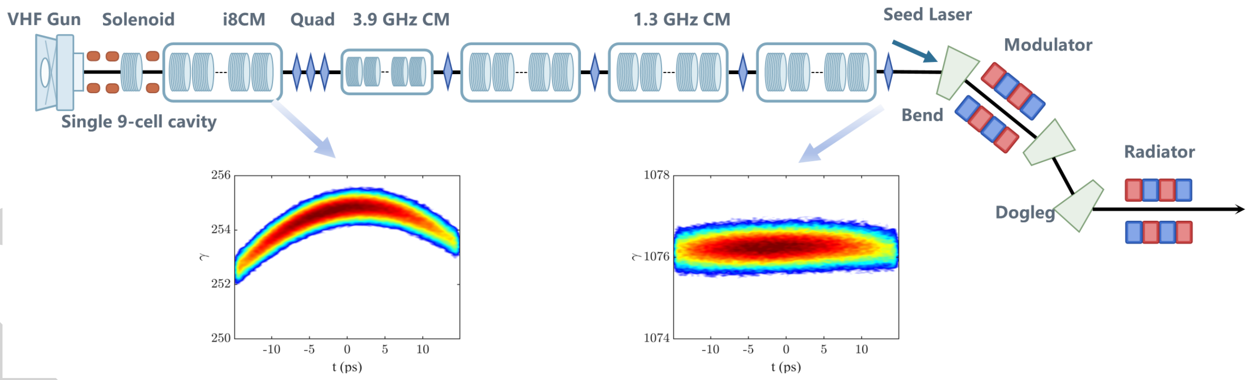

Figure 1: Layout of the proposed source, together with the longitudinal phase-space distributions after the injector and after the main linac.

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Table 1: Main Electron Beam Parameters

Parameter	Value	Unit
Energy	550	MeV
Repetition rate	10	MHz
Bunch charge	10	pC
Average current	0.1	mA
Peak current	0.5	A
Pulse duration (FWHM)	20	ps
Normalized emittance	0.15	mm·mrad
Relative energy spread	0.01	%

The main electron beam parameters are summarized in Table 1.

The ADM section consists of a bending magnet, a modulator, a dogleg, and a radiator. The bending magnet introduces the required angular dispersion before the beam enters the modulator. In the modulator, the seed laser imprints an energy modulation on the electron beam, which is then converted into high-harmonic density modulation by the following dogleg. Finally, the microbunched beam is transported into the radiator to generate coherent harmonic radiation.

The bunching factor at the n-th harmonic can be written as

$$b_n = J_n\left(nk_s\xi_D\frac{\Delta\gamma}{\gamma}\right)\exp\left[-\frac{1}{2}\left(nk_sD_x\sigma_{x'}\right)^2\right], \tag{1}$$

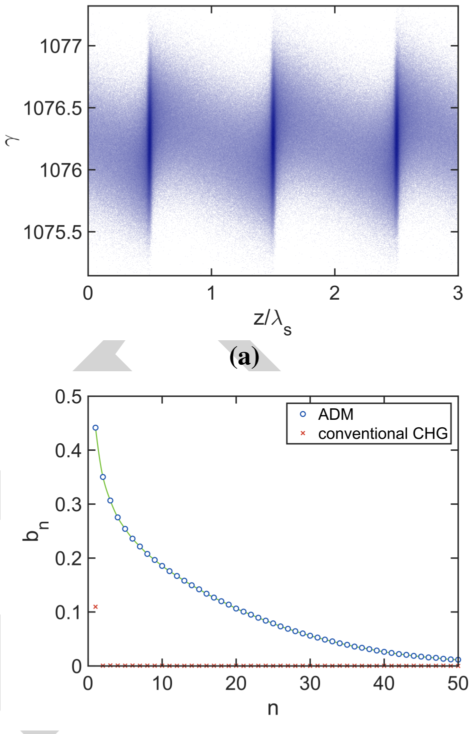
where k_s is the seed-laser wavenumber, $\Delta\gamma/\gamma$ is the relative energy modulation amplitude, ξ_D and D_x are the longitudinal and transverse dispersions, and $\sigma_{x'}$ is the horizontal rms angular spread. Equation (1) indicates that the bunching is driven by the energy modulation and longitudinal dispersion, while its high-harmonic suppression is governed by the transverse angular spread. Thus, ADM transfers part of the sensitivity from the longitudinal energy spread to the more stable transverse phase space, helping to preserve effective microbunching for narrow-band coherent radiation.

SIMULATION RESULTS

To cover the photon-energy range of interest for ARPES, seed lasers at 1064 nm and 355 nm are used, corresponding to the fundamental and frequency-tripled wavelengths, respectively. To verify the performance of the proposed scheme, simulations of the modulation and radiation processes were performed using *GENESIS* [7]. The 1064 nm seed covers the lower-energy range, while the 355 nm seed extends the tunability toward higher photon energies, enabling broad coverage of 10–100 eV. A 4-m-long U68 undulator is used as the modulator for both seed-laser configurations. A 4-m-long dual-period radiator is adopted, with the U40 section driven by the 1064 nm seed and the U25 section driven by the 355 nm seed. The main simulation parameters for the ADM section are summarized in Table 2.

Table 2: Simulation parameters for the ADM section

Parameter	Value	Unit
Bend angle	0.3	rad
Modulator length	4	m
Seed wavelength	1064/355	nm
Seed pulse duration (FWHM)	20	ps
Seed peak power	150	kW
Radiator period	40/25	nm
Radiator length	4	m



(a)

(b)

Figure 2: (a) Longitudinal phase-space distribution at the exit of the dispersion section. (b) Comparison of the bunching factors of ADM and conventional CHG.

Taking the 355 nm seed-laser case as an example, Fig. 2(a) shows that a seed peak power of 150 kW induces an energy modulation of about 0.6 times the initial slice energy spread after the ADM section. For a 20-ps pulse duration and 10-MHz repetition rate, the corresponding average laser power is about 30 W, which is feasible with present high-repetition-rate laser technology. Under the same modulation depth, conventional CHG produces negligible high-harmonic bunching. In contrast, ADM gives a bunching factor of about 5.6% at the 30th harmonic. Even at the 43rd harmonic, the bunching factor remains above 2%, as shown in Fig. 2(b).

Furthermore, we scanned the 8th–43rd harmonics of the 1064 nm seed and the 8th–30th harmonics of the 355 nm seed. The two seed-laser configurations together cover the target photon-energy range. Figure 3 shows typical pulse profiles and spectra for the simulated harmonics. The radiation power grows steadily along the radiator, and the output pulse maintains a long temporal envelope, resulting in narrow and stable spectra.

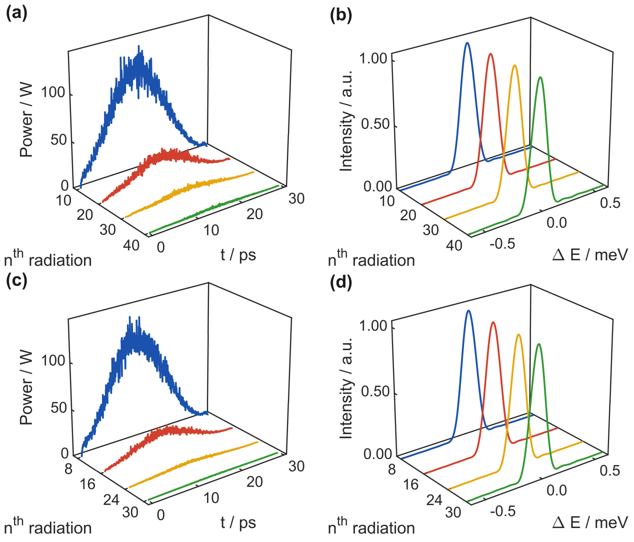
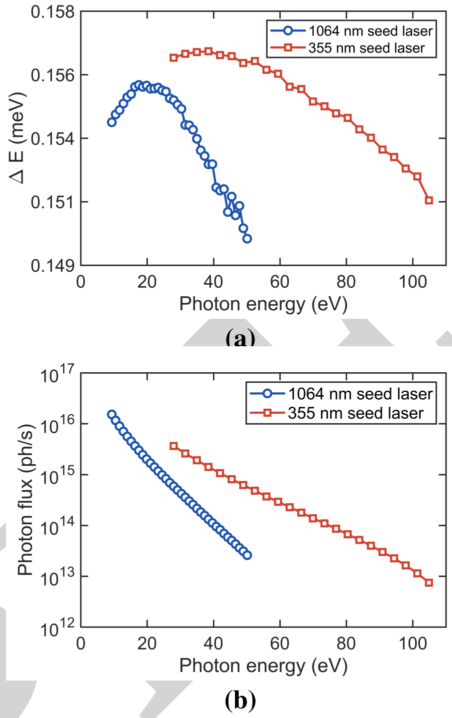


Figure 3: (a,b) Temporal pulse profile and corresponding spectrum for the 1064 nm seed. (c,d) Temporal pulse profile and corresponding spectrum for the 355 nm seed.

The photon flux and FWHM spectral bandwidth over the investigated photon-energy range are shown in Fig. 4. In the low-photon-energy region, which is particularly important for ARPES measurements near the Fermi level, the 1064 nm seed provides dense energy points with a spacing of about 1.17 eV. The 355 nm seed extends the coverage to higher photon energies with a spacing of about 3.49 eV. The output bandwidth remains at the sub-meV level across the full tuning range, with a typical value of about 0.154 meV.



(a)

(b)

Figure 4: (a) FWHM spectral bandwidth as a function of photon energy. (b) Average photon flux as a function of photon energy.

Although the photon flux decreases at higher harmonics, it remains above 10^{12} photons/s even at the highest photon energy. These results show that the proposed dual-seed ADM source can cover a broad photon-energy range while maintaining narrow bandwidth and high average flux.

CONCLUSION

In this paper, we propose a 10-MHz ADM-based coherent light source tailored for high-resolution ARPES applications. The source combines a 550-MeV electron beam with the ADM mechanism to generate narrow-band coherent radiation over a broad photon-energy range. Start-to-end simulations demonstrate that the source delivers an energy resolution of approximately 0.154 meV while maintaining a photon flux exceeding 10^{12} photons/s across the operating range. These results indicate the potential of the proposed source for high-repetition-rate, high-resolution spectroscopy.

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